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DEVELOPMENT OF A MANUFACTURABILITY ANALYSIS SYSTEM FOR REINFORCED PLASTICS COMPONENTS

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ABSTRACT

This thesis describes the research and development of a systematic and consistent methodology to perform manufacturability analysis of Reinforced Plastic Parts (RPP). The proposed methodology evaluates the part model in the early stages of the product development process considering the capabilities and constraints of available manufacturing processes, materials and tooling required in standard RPP production.

Critical Manufacturing Part Features (CMPF) are identified and the relationship between the model's geometrical information, the expert's geometric reasoning, and the knowledge about the involved manufacturing processes are clarified and set together in an efficient feature-rule-based manufacturability analysis system.

The prototype system named 'FEBAMAPP', combines solid modelling (SM), automatic feature recognition (AFR), object oriented programming (OOP), and a rule-based system (RBS) in order to assess the manufacturability of the proposed design. The novelty of this research is based in the use of a Face Vector (FVector) concept to transform geometrical and topological information of the solid model into a suitable input data to be used in the Neural Network Feature Recognition System. Further novelty arises from the fact that this is the first attempt to use neural networks in the recognition of 3-D features in hollow parts including the presence of fillets along the edges of the part.

The manufacturability evaluation can be performed considering different combinations of materials along with different manufacturing processes giving the designer the opportunity of selecting an appropriate combination for any specific application. Promising results have been obtained during the test of the system, where 100 % recognition of trained features with 90% confidence has been achieved. Also, good results have been obtained in the recognition of non-trained features such as the Cross-Slot feature, which is recognised as a Slot feature. After automatic feature recognition, Manufacturability Analysis is focused on internal and external characteristics of the model's features, where potential manufacturing difficulties are identified and feedback in terms of design suggestions is then used to advise the design process and improve the overall manufacturability of the part. This manufacturability evaluation in terms of internal and external characteristics of the features has proved to be efficient in detecting detailed design errors that can be costly in further manufacturing stages in the product development process.

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NOTATION

A - area supporting the load.

A_t - adjacency relationship among faces, edges and vertices.

$a_j(t)$ - activation of neuron j in step t.

$a_j(t+1)$ - activation of neuron j in step $t+1$.

Cx - number of convex edges converging into a vertex.

Cc - number of concave edges converging into a vertex.

ES - expert systems

E_S - Edge score

E_g - edge geometry information.

E_i - score of the edges converging into a vertex.

$f_{act}()$ - activation function.

F_g - face geometric information.

F_g - face geometric score.

F_g - face geometric information.

FGV - face geometric value of the current face being evaluated.

F_S - total face score.

$g(...)$ - function depending on the activation of the neuron and the teaching input.

$h(...)$ - function depending on the output of the preceding neuron and the current weight of the link.

i - index of a predecessor to the current neuron j with link w_{ij} from i to j.

j - index for some neuron in the network

k - index of a successor to the current neuron j with link w_{jk} from j to k.

m - total number of edges converging into the vertex.

n - number of vertices on the face.

$net_j(t)$ - net (total) input in neuron j in step t.

NV - number of vertex in the face under evaluation.

N_v - normalised value of the Face Score.

o_i - output of the preceding neuron i.

o_j - the output of neuron j.

$o_i(t)$ - output of neuron i in step t.

$o_j(t)$ - output of neuron j in step t.

P - load applied.

S - allowable stress for the material.

t_j - teaching input, in general the desired output of neuron j.

t - thickness of the part.

V_g - vertex geometry information.

V - vertex score.

VV - vertex value.

VVi - vertex value of the vertex i.

w - width of the section supporting the load.

w_{ij} - weight of the link from neuron i to neuron j.

ΔW_{ij} - change in the weight of the link from neuron i to neuron j.

δ_j - error or difference between the real output and the teaching input of neuron j.

η - Learning-factor constant.

θ_j - threshold or bias of neuron j

Chapter 1

1 INTRODUCTION

1.1 Design for Manufacture

Traditionally, design and manufacturing have been treated as two separate functions in the product development process, but new design technologies and better computer resources are opening opportunities to link them. Also, traditional methods of developing products suffer from a lack of information at the later stages of the development process where the early decisions have a major influence increasing the lead-time and impacting on the allocation of the project resources (Ching and Wong, 1999).

Affordability of composite products, though largely associated with cost saving measures in manufacturing, is significantly influenced by their design (Pochiraju, et al, 1998). Most of the problems associated with development of reinforced plastics components could be avoided if the design team is able to make the early decisions with sufficient consideration of aspects such as available manufacturing processes, matcrials, tooling and labour.

One of the main goals of Concurrent Engineering (CE) is to reduce the cost incurred in product development by conceiving design, installation, organisation and control of production activities as a whole (De Martino and Giannini, 1998). This should be done in such a way that all decisions to be taken could be evaluated in relation with each other during the design phase.

Furthermore, detailed information of product concepts is normally not available at early development stages, and thus decisions are made using qualitative information and judgement, requiring expert knowledge to direct the evaluation of the proposed design alternative (Rosenman, 1993). In traditional practice the product concept development depends on human experts, such as product designers, tool designers and manufacturing engineers who are required to have a high standard of specific knowledge, experience and judgement.

The planning and design functions can be performed very well by Knowledge-Based Systems (KBS) in the engineering and manufacturing areas of product design (Ignizio, 1991). Product concept development and evaluation is predominantly based on the experience of designers, where extensive mathematical analysis is not often applied since analytical models are not available and calculations are often limited to those satisfying empirical rules. Consequently, designers are required to have a high standard of general knowledge and judgement.

Current KBS applications to assess the plastics product design are relatively new and few in numbers. Research topics for capturing injection moulding part design features from a Computer Aided Design (CAD) models, advising plastic material selection, automating the mould design process, etc., have become popular.

It has been recognised that feature-based modelling can bridge the gap between engineering design and manufacturing (Shah and Rogers, 1988; Shah, 1991; Gadh, 1995; Ling and Narayan, 1996; Vosniakos, 1998; Jha and Gurumoorthy, 2000). All these authors have reached the conclusion that the information required by the different domains involved in new product development processes requires a common linkage among these domains so the product development cycle can be reduced. This linkage, in the form of features, can facilitate the automation of the design to manufacture process.

The process of recognising manufacturing features from a CAD model may consist in checking a specific set of model's entities against a pattern or set of rules. This approach had been used in previous works (Jagirdar, et al, 1995; Chamberlain, et al, 1993; De Martino, et al, 1994; Allada and Anand, 1997), where it had been pointed out that those manufacturing features are application dependent. Therefore, manufacturing features for reinforced plastic components must be defined in such a way that they can support a feature recognition process.

The lack of support from CAD and Computer Aided Manufacturing (CAM) in the reinforced plastics industry is the major motivation of this research. Critieal Manufacturing Features (CMF) are identified and the relationship between the model's geometrical information, the expert's geometric reasoning, and the knowledge about the manufacturing processes involved are clarified and set together to produce an efficient manufacturability analysis system, named Feature-Based Manufacturability Analysis of Plastic Parts (FEBAMAPP).

1.2 Aim of the Research

The Venezuelan National Committee for Research, Science and Technology (CONICIT) board has funded this research, with the objective of giving support to the growing reinforced plastics manufacturing industry in Venezuela. There are more than 300 companies registered with the Venezuelan Association of Reinforced Plastics Manufacturers (AVENPLAR) where 85% of them can be considered as small and medium size manufacturing enterprises (SMMEs). Due to the fact that usually there is a limitation in the technical support, in terms of hardware and software, in the SMMEs of developing countries, then it is of great importance for the success of the intended system to be able to run on low performance computers.

Therefore, the aim of this thesis is to develop a feature-based methodology to perform manufacturability analysis on reinforced plastic components. This is intended to give support to SMMEs that are dedicated to the manufacture of reinforced plastics components.

Furthermore, this research aims to demonstrate that a three-layer perceptron Neural Network (NN) can be trained to perform automatic three-dimensional (3D) feature recognition on filleted models of reinforced plastics parts.

1.3 Research Goals

The main goal of this research is to establish a methodology to perform manufacturability analysis of reinforced plastic components by using a hybrid system including automatic feature recognition and a feature-based assessment of manufacturability.

Another goal of the research is to develop a technique to represent geometrical and topological data of a 3D solid model's Boundary Representation (B-Rep) in such a way that it facilitates the automatic feature recognition process using an NN system. An NN system will be trained using a supervised learning algorithm by presenting the network with sample parts containing relevant features related to the reinforced plastic manufacturing process.

Additionally, a methodology will be developed to perform a rule-based manufacturability analysis by comparing model's features characteristics with a collected set of manufacturing and design rules. The intended output of this analysis is the evaluation of the model in terms of manufacturability of its features and a series of guidelines for its design regarding characteristics associated with specific reinforced plastics manufacturing processes.

1.4 Thesis Structure

The final modular architecture of the FEBAMAPP system will be used to describe the sequence of events required to perform the manufacturability analysis of a proposed design. The actual architecture of the system is presented in Figure 1, where a colour code is used to identify the different modules in the system as follows:

- Pre-processing of the SAT file,
- Automatic feature recognition,
- Post-processing of the SAT file,
- Material selection,
- Process selection,
- Manufacturability analysis, and
- Report

The modules perform sequential tasks where the output of a previous module is used as the input of the next module in the process. This modular design approach used in the design of the system allows considering the key aspects of the research in a separate way but keeping the links between the different areas of knowledge involves in the development of the system. Furthermore, the modular architecture allows an easy way of performing update of each module in the system when it is required without need of modifying the other modules.

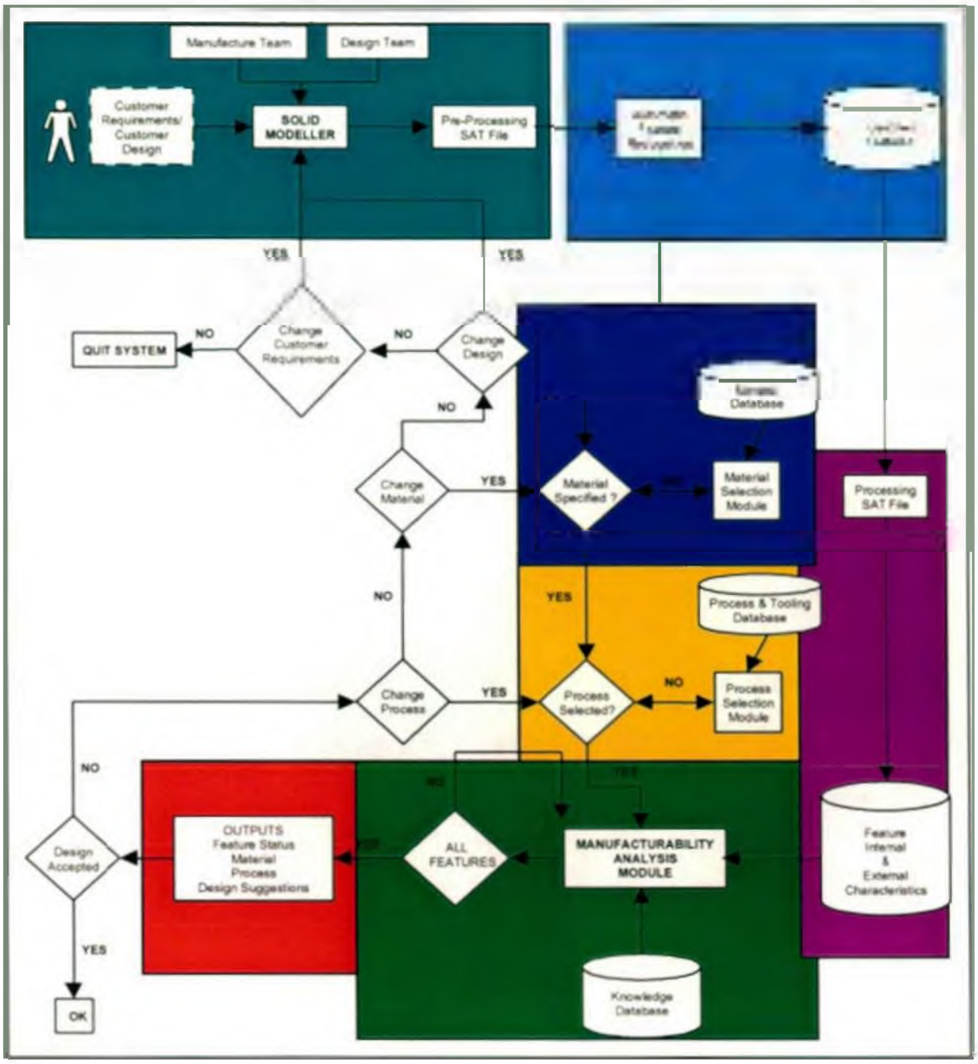


Figure 1. Modular structure of the FEBAMAPP system.

Following the natural flow of information in the system it is possible to observe that the whole process of manufacturability analysis starts with the creation of the SAT file based on the information stored in the database of the solid modeller used to create the model of the part. This database contains basic information regarding the specifications of the part from the design point of view, such as dimensions, tolerances and shapes. Once the SAT file is created, the [redacted] of FEBAMAPP will create the required data structures and will transform the geometrical and topological data of the model into a series of Face Vectors

(FVectors) to be used as input in the module of automatic feature recognition. The key aspect of research corresponding to this module is identified as the codification of the solid model information in such a way that it facilitates further use of this information in the automatic feature recognition process using an artificial neural network system.

The automatic feature recognition module uses the FVectors as input in the ad-hoc neural network (NN) system, which are in charge of performing the recognition of the features present in the model. The output of this module is in terms of tag numbers identifying the main faces of each feature in the model, along with the other identifying tag numbers of the remaining faces forming the feature. The key aspect of research corresponding to this module of FEBAMAPP is identified as the architecture design and training of an appropriate NN suitable to solve the feature recognition problem of this particular application.

The following step in the process corresponds to the post-processing of the SAT file. This module takes as input the tag numbers identifying the faces corresponding to each feature identified in the model and uses this information to search in the original SAT file the necessary information required to perform the evaluation of each feature. The output of this module is in terms of dimensions, angles, normal vectors, radius, etc. all of them are considered as internal and external characteristics of the feature to be evaluated. The key aspect of research in this module is the processing of the SAT file in such a way that it allows the comparison of the actual dimensions of each face in the features with the dimensions stored in the database of FEBAMAPP as the target values for the feature evaluation.

Materials selection is the next module in the system. Options are presented to the user in terms of resin and reinforcement materials available in the system. A particular selection of materials combination will determine the limitations and constraints in terms of the manufacturing process that can be used in the manufacture of the part. Therefore, it is clear that the materials selection drives the options of available manufacturing processes to perform the manufacturability analysis. The main reason supporting this decision is that not all materials are suitable to be used on all reinforced plastics manufacturing process. Once the materials are chosen then the options of available manufacturing process for that particular combination of materials is presented in the process selection module. The key aspects of research in these two modules are related to the search for information regarding materials and manufacturing process, and their limitations and capabilities from the point of view of manufacture. This information is of capital importance in the following module where the individual evaluation of the features is used as the base for the manufacturability analysis of the model.

The [redacted] has two basic components. The first one is the knowledge database of the system, where all the production rules corresponding to each feature supported in the system are stored. The second component is the core of the manufacturability analysis module or inference engine, it is in this component of the module where all comparisons between the actual internal and external characteristics of the features and the values stored in the knowledge database are carried out. Input to this module is in terms of the actual features geometry, materials capabilities and limitations, manufacturing process constraints if there are any in relation to the materials to be used, and the information stored in the knowledge database. A binary output is expected in this module where a feature could pass or fail the evaluation. Also, information regarding the faces that fail to pass the evaluation is generated in this module and passed to the report module. The key aspect of research identified in this module is the integration between the different modules and the inference engine of the system. Also the design of the interface with the user is considered in this module of the system.

Finally, the [redacted] completes the set of modules in the FEBAMAPP system. This module takes the information given by the manufacturability analysis module and creates a written report of the analysis including the faces that fail to pass the analysis and the status of each variable considered during the analysis. Also, this module creates a series of SAT files where a colour code is used to represent each face in the model and to highlight those faces that fail to pass the analysis.

There is a feedback facility built-in the system, which allows the user to step back at each stage of the analysis and change the parameters being used for the manufacturability evaluation of the model. The user can change materials and manufacturing process inside the FEBAMAPP system to try different options during the early design stages of the product development process. Changes in terms of the geometry of the model must be carried out in the solid modeller being used to create the model, and a new pre-processing of the SAT file is required before making further manufacturability analysis of the new model.

The actual structure of the thesis tries to follow the natural sequence of events described previously and the flow of information in the FEBAMAPP system. The thesis has nine chapters which contents are described as follows:

- Chapter one presents the aims of this thesis along with the research objectives and a brief introduction about the design for manufacture topic. Also, it includes a description of the thesis structure and the sequence of events followed during the manufacturability analysis of a particular model.

- Chapter two contains a review of current literature performed as part of this research, where previous work in the key areas of research identified in chapter one are considered. The main areas considered are expert systems, feature technology and feature recognition processes where basics and modern trends in current research are pointed out. Also, this chapter presents basic information regarding reinforced plastic manufacturing process, current approaches of manufacturability analysis and a brief introduction to neural computing and its principles.

- Chapter three gives the conceptual framework of this research, where a computer-based modelling representation and CAD representational schemes are discussed. Also, design parameters of reinforced plastic components are presented as the basis for the manufacturability analysis system to be developed. Finally, some principles of manufacturing process selection are presented.

- Chapter four presents the basis of the feature recognition process including the principle concepts of face graph, face score and face vectors along with the features definition. Furthermore, this chapter also includes details of development and training of the neural network system used for automatic feature recognition in reinforced plastic components.

- Chapter five contains specific information regarding design parameters of the features being considered in this research. Also, important information about capabilities and limitations of manufacture processes commonly used in the manufacturing of reinforced plastic parts. This chapter presents the basis for developing the rule-based manufacturability analysis system and it includes a sample of the production rules applied to the evaluation of the Boss feature. The full set of the production rules developed, as part of this research, is included as a separate confidential document in the back pocket of the thesis. This material should be detached from any public copy of the thesis.

- Chapter six contains the framework of the manufacturability analysis system and its implementation details. Also, a sample run of FEBAMAPP is included in this chapter.

- Chapter seven presents results of the current research, where several sample parts are used to point out FEBAMAPP capabilities and performance of recognition and manufacturability evaluation of the features. This chapter includes a thorough analysis of the results focusing on three main aspects of the research: object representation, feature recognition and feature evaluation.

- Chapter eight presents the main conclusions of this research and some suggested developments or extensions of the present work. Also, some limitations of the system are pointed out in this chapter.

- Then it follows a comprehensive list of references used during the development of the system.

- Finally, the appendices contain supportive material, which hopefully will help to illustrate the whole process of manufacturability analysis including feature recognition and feature evaluation as it is presented in this thesis.

As part of the research process several research papers were presented in National and International conferences, Appendix 5 presents a copy of these papers. Also two papers were published in recognised Journals. The chronologically ordered list of the technical papers produced as part of this research is as follows:

- Marquez, M., Gill, R., and White, A., 1999, "***Application of Neural Networks in Feature Recognition of Mould Reinforced Plastic Parts***", Concurrent Engineering: Research and Applications, Volume 7, No 2, pp 115 – 122.

- Marquez, M., Gill, R., and White, A., 1999, "***Hybrid Text File – Neural Network Feature Recognition System***", 15th International Conference on CAD/CAM, Robotics and Factories of the Future, Aguas de Lindoias, Brazil, Volume 2, section Computer Aided Design, pp CW2 - 1 to CW2 -5.

- Marquez, M., Gill, R., and White, A., 1999, "***Automatic Feature Recognition on Plastic Components***", Advances In Manufacturing Research XIII, Proceedings of the 15th National Conference on Manufacturing Research, University of Bath, pp 435 – 439.

- Marquez, M., Gill, R., and White, A., 2000, ***"FEBAMAPP: Feature-Based Manufacturability Analysis of Plastics Parts"***, 16th International Conference on CAD/CAM, Robotics and Factories of the Future, Advanced Manufacturing and Engineering Centre. The University of West Indies, St. Augustine, Trinidad W.I. pp 394 – 402.

- Marquez, M., Gill, R., and White, A., 2000, ***"A Hybrid Neural Networks – Feature Based Manufacturability Analysis of Mould Reinforced Plastic Parts"***, Journal of Engineering Manufacture, Proceedings of the Institution of Mechanical Engineers Part B. (This Journal Paper has been accepted for publication and it is in press at the moment).

Chapter 2

2 LITERATURE REVIEW

Based on the aims and goals of the research as they were set on the previous chapter, it is possible to identify a number of key areas in this research work and it is intended in this chapter to explore previous work in such areas.

The intended manufacturability analysis system to be developed falls into the field of expert systems or knowledge-based systems. Therefore, the structure of such systems and the modern trends for developing them including knowledge representation will be explored in the current literature. It had been determined that several factors have an important role in successfully implementing a new expert system. Those factors are closely related to problem characteristics, developer skill and domain of expertise, end-user characteristics, framework characteristics and user involvement (Guimaraes, et al, 1995).

A second key aspect identified in this research is the feature technology and feature recognition processes, which will be outlined in this chapter and modern techniques will be pointed out. Since the use of NN technology is intended for the feature recognition module of the proposed manufacturability analysis system, then a section will be included regarding NN basic concepts and training algorithms.

Finally, it is very important to have a complete understanding of the basic concepts regarding reinforced plastic manufacturing process and the current approaches of manufacturability analysis. Therefore, information related to the most common manufacturing process used in the SMMEs dedicated to the manufacture of reinforced plastics components is included, where important aspects to be considered during the manufacturability analysis are pointed out.

2.1 Expert Systems

The term Expert System refers to systems, which comprise at least four elements. Firstly, a knowledge database of the process to be modelled in the form of abstract knowledge and specific facts. Secondly, an Inference Engine (IE) in charge of applying abstract knowledge to specific facts such that the system can reach a conclusion. Thirdly, an explanation module, which will give the user information about the process followed by the system to reach the conclusions. Finally, a user-interface to allow the communication between the user and the system. All four components interact in order to mimic human expert decision-making.

Expert systems have the immense advantage of providing ready access to specialist knowledge of the sort, which usually would be only available, if the genuine human expert were present. They allow non-specialists to process information and make decisions that they would not normally be able to. Also allowing unlimited duplication of the real expert and extending the real expert knowledge by means of learning process.

There are disadvantages to expert systems as well. They take time to develop and also they can be expensive. Expert systems are also clearly more adapted to certain limited ranges of human information. Expert systems are not a universal tool that can be applied to any problem.

2.1.1 Knowledge representation

Knowledge representation of a particular domain in an expert system should have several properties. Firstly, capacity to represent all kinds of knowledge required in the domain. Secondly, be able to manipulate the structures of knowledge representation in such a way that new structures can be obtained and used to represent new knowledge deducted from the previous one. Thirdly, be able to easily obtain new information (Rich and Knight, 1994). Unfortunately, there is not a system able to optimise all those aspects and be applicable to all kind of knowledge but there are a wide number of options to represent knowledge. The efficient operation of an expert system will depend upon the way in which its information is stored and how it is made available to the system user (Hall, 1989).

Currently there are four main methods of knowledge representation employed. These are frames, scripts, semantic networks and production rules. They can be used separately or in combination with one another (Castillo and Alvarez, 1989).

A frame is a table of information on a particular subject. Individual entries on the table are called slots. Four types of slots may be incorporated into a frame. One type simply states a particular piece of information appropriate to the subject. Another type, a default slot, will contain an inevitable piece of information. A procedural attachment slot defines a routine or procedure needed to determine further information for the frame. Finally, a reference slot links the current frame with another, which contains relevant further information about the subject. Reference slots allow a hierarchy of frames to be constructed, thus building up a broad knowledge base.

A script is very much like a frame, in that it stores detailed and fairly specific information. Unlike a frame, however, it describes a process rather than specific subjects. Variations in a script are 'tracks'. 'Roles' are the principal characters involved and 'props' are objects. 'Scenes' relate the actual process in order. 'Entry conditions' trigger this part of the overall script. 'Results' show the final situation and may match the entry conditions that will trigger another track of the script.

A semantic network is an easily comprehended way of representing information. It is simply a network of nodes containing related items linked by arcs representing their relationship. It seems that semantic networks can be incorporated in a very useful way into an expert system and allow sensible decisions to be made. Nevertheless, one of the major drawbacks of semantic networks is the fact that the arcs can represent different kinds of relations between nodes.

The method most often used for storing information in an expert system is to include a large set of IF-THEN clauses, known as production rules. These allow sequences of decisions to be made and logical consequences to be inferred. Each production rule in a knowledge base implements an autonomous chunk of expertise that can be developed and modified independently of other rules. When combined and fed to the inference engine, the set of rules behaves synergistically, yielding better results than that of the sum of the results of the individual rules (Turban, 1998). This particular author points out the main aspects to be considered during the creation of the production rules, the links between different segments of knowledge and the triggering of each set of rules.

Production rules were used in this research because they can be especially easy to understand and they can be viewed, in some sense, as a simulation of the cognitive behaviour of human experts in the field of reinforced plastics. The use of this approach will allow development of specific sets of rules for each feature to be evaluated by FEBAMAPP system and combining together all sets will improve the overall evaluation of a proposed model.

2.1.2 The inference engine

The part of the expert system, which does the reasoning, is known as the inference engine. This draws upon both the stored knowledge and replies from the user of the system in order to reason its way through to an answer. In a production rule system, two types of inference can be made, forward chaining, and backward chaining.

In backward chaining, the system begins with the required answer (goal-driven approach) and then searches through its production rules to seek out what prior conditions would be required. Again it eventually arrives at a set of ultimate clauses, which are necessary for the final state, and it seeks to match these against the details provided by the user. The path of true conditionals, which will be followed by the relevant arcs in the network, can become very complicated. Nevertheless, the algorithms employed by the inference engine have to be able to cope with such complexity.

In forward chaining the inference engine begins with the information currently provided by the user (data-driven approach) and draws conclusions, according to the conditional rules that it knows already. During this process, it may request further details from the user. Eventually, it will arrive at logical consequences, which it then gives as its decision. FEBAMAPP uses forward chaining because it seems to be more appropriate to the kind of information available to the system and the sequence of events to be carried out during the features evaluation process.

A problem faced in building expert systems is found in entering all necessary information that is required for its decision-making. It is a long and very tedious process to obtain all of the knowledge required from a human expert. Mistakes can be made in transferring data from mind to program. Repeated adjustment will be required to the expert system in order to check that the new rules are behaving as expected. This will inevitably be very time-consuming (Monostori and Egresits, 1997).

In a more subtle way, many of the vital processes involved in the human expert's decision making may not actually be obvious to the person involved. This is essentially one of the problems facing anybody who is trying to code a human expert's skills into computer software (Preece, et al, 1997). To overcome this problem the experts closely worked with the system development team, and a close supervision of the whole process of production rules creation was maintained at every stage of the research.

2.2 Feature Technology

CAD systems typically represent the manufactured part as solid models. However, the CAD database represents the geometry and topology of the part model in terms of low level product definition, such as surfaces, edges and vertices. The low level product definition makes it very difficult to perform Automated Engineering Analysis (AEA). The power of AEA can be exploited to its fullest extent if the input from the CAD data is in higher-level form such as 'features'.

Feature-based systems have demonstrated some potential in creating interactive design environments and in automating the geometric reasoning necessary in applications such as manufacturability evaluation.

The term 'feature' is very context dependent. For the same part model, manufacturing features, assembly features, finite element modelling features, etc., might not be the same. The term 'feature' can be understood as "*a mathematical function of some topological and/or geometric variables whose values can be readily accessed or derived from the solid model of the part*" (Prabhakar and Henderson, 1992). Furthermore, manufacturing related features can be defined, without restrictions, as "*regions of a part with some manufacturing importance*"

(Allada, V. and Anand, S., 1997). Though the numbers of features in a particular application are infinite, the good news is that they can be categorised into a finite number of classes. As part of this research a definition of main features relevant to the manufacturing of reinforced plastics components need to be created. This definition of features should include information regarding the geometry of the feature and the limitations naturally linked to the materials and manufacturing processes to be used in the production of the parts.

A Feature Based Design System (FBDS) can be seen as an auxiliary module to an existing solid modelling system where the part representation can be obtained in one of three ways. Firstly, the user could interactively identify the presence of features in the part model. Secondly, the user can construct the part model using features. This approach is referred to as feature based modelling or design by features. Thirdly, features in the part can be extracted automatically, given the part model. This approach is known as automatic feature recognition.

In the design by features approach, information is stored during the design phase of the part model. The designer creates the part model using features present in the feature library. This prevents the need for feature recognition from the part model. However, the design by features approach has its own drawbacks. Firstly, all the possible features for any application cannot be stored in the feature library. For this reason this approach has been used over a narrower application domain, where features are defined as application-dependent. Secondly, feature validation needs to be performed each time a new feature is added to check if the new feature is properly placed or if the new feature distorts the validity of existing features. Thirdly, the system calls for expertise on the designer to choose the best set of features to model the part. Fourthly, design by features is a constraint for the designer creativity by restricting him/her to the features present in the feature library. Nevertheless, parametric design can be used to represent family of features giving to the designer a wider range of feature selection.

According to Jha and Gurumoorthy (2000), if the feature representation of the part has to be realised through feature based modelling, then the user has to construct the part for each task using the set of features appropriate for the task domain. This statement implicates that design by features negates the whole purpose of introducing the concept of features into the design process.

Since both design by features and automatic feature recognition approaches have their own advantages and disadvantages, it is necessary to perform a careful analysis before deciding which one is more appropriate for any specific application. Some of the variables that must be considered in this analysis are:

- Availability of commercial software,
- Hardware requirements,
- Time for system development,
- Designer limitations,
- Training of users, and
- Interaction with other application software.

It is of particular interest in this research to consider the target users and market of the manufacturability analysis system to be developed as they were mentioned in the aims of the research. Therefore, commercial software able to run in low performance personal computers with limited availability of hardware, are considered as the first option in developing the application. Keeping the system as simple as possible may help to reduce or minimise the need for training of the system users. Also, a straight forward interaction between FEBAMAPP and the solid modeller used to create the solid model of the part to be analysed will reduce the training of the user and facilitate the incorporation of the system in the product development process.

2.3 Feature Recognition Processes

Feature recognition is a necessary and important component to support the automation from design to manufacture. It provides a link between design and manufacturing-related downstream applications. The main advantage of using features is that they make it easy to perform manufacturability evaluation early in the design process (Narang, 1997).

Previous work in feature recognition systems can be classified into human-assisted feature recognition and automatic feature recognition. In human-assisted feature recognition systems there is considerable human intervention in all stages of the recognition process. In automatic feature recognition systems, the recognition and extraction stages are completely automated. Automatic feature recognition algorithms can be further classified into machining-region, rule-based, graph-based, Constructive Solid Geometry -based and application-based algorithms.

Machining-region recognition typically assumes that milling will do all machining, and so it is not necessary to know the specifics of a feature, other than its boundaries corresponding to the final machined surfaces. Most of the work in this area seems to have been focused on 2-1/2 D milling and the generation of tool paths for numerical controlled machined processes.

Automatic feature recognition systems recognise features after the part is modelled with a CAD system. Recognition is made using the geometric and topological information of the CAD database. Typically, a specific geometry/topology configuration is searched in the part model to infer the presence of a particular type of feature. These systems usually have complex algorithms.

The process of feature recognition comprises three major tasks:

- Feature definition, in which the rules for recognition are specified,
- Feature classification, in which potential features are classified, and
- Feature extraction, in which features are extracted from the solid model, and stored for further analysis.

This research gives special attention to application-based automatic feature-recognition algorithms based on B-Rep representational schemes. Nine approaches had been identified by Onwubolu (1999), which include: syntactic pattern principle, geometric reasoning and pattern matching, generate and test, alternating sum of volume, attributed adjacency graph, differential depth filter, expert systems, hybrid rule-based/graph based and neural networks.

Kyprianou (1980) applied syntactic pattern principle to recognise the rotational part features and subsequently classified the parts using group technology (GT) concepts. Other researchers that later used syntactic pattern recognition concepts for part feature identification include Choi (1982), and Chuang and Henderson (1990). The use of syntactic pattern approach was based on a shape grammar that used a convex/concave classification of the edges, vertex and loops in the part. Faces were marked as primary if they contained a concave edge or an inner loop, and primary faces were ordered on the basis of the number of concave edge sets. An ad-hoc language was developed for specifying GT schemes and constructing the GT code.

Nnaji et al, (1991), have developed a feature recognition system for recognising features from sheet-metal parts using a combination of geometric reasoning and feature pattern matching techniques in two different levels. The first level is geometric reasoning between feature classifications, which allows determining the general characteristics of the features, while the second level is pattern matching based on the feature patterns stored in the system database used to recognise domain-specific features. The second level of pattern matching has the constraint of using a 'testing feature' graph to match a 'pattern feature' graph, which must be isomorphic to each other. Two graphs are isomorphic not only when based on the adjacent relationship of the nodes, but also when all the information carried in the nodes and linkages is the same. Matching those graphs and establishing that they are isomorphic to each other requires resorting to an exhaustive search procedure that is highly demanding on the system.

Woo (1984) suggested a method for machining volume extraction using the convex-hull and difference operator, called the alternating sum of volumes (ASV) method. The ASV method represents an object by a series of convex objects with alternating signs for volume addition and volume subtraction. This is an efficient method for machining components but it is unusable in moulding applications.

Graph-based approach to feature recognition has been employed by several researchers such as Sakurai and Gossard (1988), Joshi and Chang (1988), Falcidieno and Giannimi (1989). Usually these approaches use the attributed adjacency graph (AAG) defined as a set of nodes, arcs and attributes such that for every face in the model there exists a unique node. For every edge, there exists a unique arc connecting the faces that share the common edge. Every arc is assigned an attribute value based on the angle between the faces sharing the edge.

The application of AAG is currently limited to polyhedral features and parts. Furthermore, since this scheme was not designed to handle specific characteristics of the features there is a tendency to mistake features; for example a straight rectangular slot and a dovetail slot are treated as the same feature. Extension of the concepts used in graph-based approach to other types of faces used in solid modellers, such as cone, sphere, and torus, need further research.

Another variation of graph-based approach is the differential depth filter technique proposed by Gadh and Prinz (1992) to reduce the search space for possible presence of manufacturing features in the model. This basic approach is not able to represent and recognise certain types of features, especially those features including fillet as later reported for Gadh and Prinz (1995).

Researchers like Henderson (1984), Kung (1984), Bond and Jain (1988) have used an expert system approach for manufacturing feature recognition. Herbert et al. (1990) describes a rule-based feature recognition system named LUMP. It was developed as a part of the 'Design to Product' (DtoP) project. LUMP is a rule-based system (about 20 rules) for converting a CSG string from the design stage into a set of features useful for the machining process planning activity. Once more, machining manufacturing reasoning cannot be easily transferred into moulding manufacturing processes. Also, Vandenbrande and Requicha (1990, 1993) used a Generate and Test strategy to build a feature recognition system based on production rules and geometric computations.

Fuh et al, (1992), devised a logic-based system for identifying features such as holes, counter-bores, pockets, slots, grooves, etc. For example, the rule for identifying the feature 'circular groove' can be written in plain English as follows:

IF

There exist a blind hole and a cylinder,
which are concentric, and
whose top surfaces lie on the same plane, and
the depth of the hole equals the height of the cylinder, and
the diameter of the cylinder is less than that of the blind hole

THEN

the feature is considered as a 'circular groove'.

Lee and Fu (1987) collected the CSG primitives, according to their spatial relationship of principal axes, to identify the features. The approach is essentially based on the manipulation of the CSG tree by using a heuristic strategy of node relocation and unification. Apparently, this technique which is based on the notion of principal axis of the feature and a scheme of node pairing is independent of the feature being extracted and unified. Nevertheless, there remains the need of carrying out an extensive and comprehensive study of a large variety of features to define each individual feature and to co-ordinate the extraction and unification of multiple features of several types. Applications of this technique in the field of moulded parts had not been reported but only on the manufacturing of machined components.

The main drawback of the previous approaches is the fact that they ask for a great deal of user interaction during the feature extraction process and they are extremely demanding in the system because the computational time grows exponentially with the number of features in the model. Furthermore, specific information regarding geometric information of the feature and its relationship with remaining features in the part are not easy to get using this verbose style.

Neural Networks (NN) can be applied to feature recognition and trained using supervised learning algorithms. This implies that they can be trained to perform tasks by presenting them with examples rather than specifying the procedure. Another major advantage of neural networks is that they are relatively robust and, if properly trained, they can perform very well on noisy or incomplete input patterns (Garrett, et al, 1993).

The first reported neural network approach using a perceptron for recognition of manufacturing features was proposed by Hwang (1991). The perceptron was a pattern classifier for only linearly separable patterns, with supervised training.

Prabhakar and Henderson (1992) have demonstrated the application of neural nets (a multi-layer perceptron approach) for recognising form features. The net used in this application consists of five layers, which behaves like a multi-layer perceptron but only in function and not in training. This means that the network cannot be trained using learning algorithms such as back-propagation, which are commonly used on the training of this class of neural nets. This approach uses as input in the learning pattern the total number of faces in the object and it is obviously unreasonable to expect the number of faces on every model to be equal. Another drawback of this approach is the fact that training is done by interactively defining features by the user by picking faces from a wire-frame image of the training parts on a computer screen, which is time consuming and prone to errors. Nevertheless, the system is capable of recognising some of the complex incomplete features such as 'hole through an edge' and 'hole through a vertex'.

In a more recent work, Chen and Lee (1998), consider using a neural network system for two-dimensional feature recognition on sheet metal parts limited to features with six-edge loops as a maximum. Also, this research assumes that the thickness of the part is zero assuming that the feature is located in a single plane. Neither consideration of face characteristics such as convexity and orientation in the space nor features with more than one edge loop is made.

Onwubolu (1999) proposes a Back-propagation Neural Network using a face-complexity-code as input, for the recognition of nine machining manufacturing features. The face-complexity code is based in the concavity and convexity of the faces, edges and loops of the model.

In machining application the final shape of the part is achieved by suppressing material, therefore the most typical application of feature recognition systems on machined parts is the process planning or sequence of operations required to manufacture such components. In general each manufacturing feature is associated with a specific manufacturing process, where some of the features may require one or more manufacturing process to be machined.

A common aspect of all the previously mentioned NN approaches to feature recognition, is that they all consider feature recognition of bulked machined components with sharp edges. One of the aims of the present research is to identify and to recognise features on husked plastic moulded parts, which made broad use of fillets to blend adjacent surfaces in the part. A fillet on a part can be defined as the surface or surfaces obtained when an edge or a group of edges are rounded. Furthermore, fillets can be considered as auxiliary features, which play an important role in determining the manufacturability of parts manufactured either using close-mould or open-mould manufacturing processes.

Recognition of features containing fillet is a difficult task. For the purpose of simplicity, most feature recognition approaches attempt to extract features from sharp edge models. Among the approaches used to solve the feature extraction problem on a filleted model, feature redefinition has been one of the most widely used. For example, Kumar, et al (1996) simplifies the model by determining all the fillets in the model and eliminating them. Either extending the planar surfaces adjacent to the fillet surface or replacing the fillet surface by a planar surface does elimination of fillets. Once more, these authors concentrate their efforts in simple cases of fillet surfaces on machining parts and more complex fillet surfaces, such as sphere, cone and torus are not dealt with.

Curvature region approach is another way to handle features with non-linear surfaces (Sonthi and Gadh, 1998). In this approach the B-Rep of the model is transformed to a higher level of representation called the Curvature Region Representation (CR-Rep). However, direct feature extraction from the model with fillet surfaces is computationally expensive because it is necessary rebuild the full model. Also, the algorithm used to identify the fillet surfaces using this approach is particularly expensive since a large number of points need to be sampled for each surface in the model.

The Virtual Edge approach suggested by Zhao, et al, (1999) replaces fillet surfaces with sharp edges thereby transforming a filleted model to a virtual sharp edge model. A sharp edge-based feature extraction approach is subsequently used to extract the sharp edge features. Finally, the sharp edge features are mapped back onto the filleted model to obtain the exact features with filleted surfaces. This approach is complex since a primary classification of the features is required based on the convexity and concavity of the model's edges and surfaces such that the fillet surfaces are identified. The next step is the construction of the virtual edge and vertex model, which includes the identified fillet surfaces in the original model. Then a further classification of the features is required, which uses topological and geometrical data of the model. Finally, a mapping from the virtual features into the original fillet model is required.

A common drawback found in the systems attempting to handle filleted models is that they are not able to handle spline surfaces, cones with non-uniform radius and sphere surfaces, which are widely used in the manufacturing of plastics components. Also, all these systems are developed to run on high performance computers or power stations, which are not suitable for the target market of this research.

The previous analysis of the different approaches already used for feature recognition of filleted models and their limitations, suggests that a different approach is required and the applications of NN technology is a promising approach.

2.4 Manufacturing Processes of Reinforced Plastics Components

Recent development in polyester resins and their reinforcing agents have led to an increasing number of processing techniques. Initially the main attraction of polyester resins was their ability to be moulded without pressure where no presses were required and were therefore less expensive moulds. Due to the limitations of the contact or hand lay-up technique many developments have been proposed and adopted over the years. These include low-pressure methods, matched die moulding, spraying and resin injection, which are associated to modern and continuous production methods. The various processes can be classified as follows:

- Contact moulding (or wet lay-up process)
    - Cold methods
    - Heat assisted methods
    - Filament winding
    - Tube manufacture
    - Spraying (or rove depositing)
- Matched die moulding (or metal die moulding)
    - Use of pre-forms
    - Use of pre-impregnated mats
    - Use of tailored fabrics
    - Extrusion (or pultrusion)
- Confined flow methods
    - Vacuum impregnation (or Marco-Vacuum method)
    - Pressure impregnation

  - Injection methods
- Casting
  - Normal casting (or encapsulation)
  - Centrifugal casting.

2.4.1 Contact moulding

Glass mats are laid on the mould and wetted-out with resin by hand or other means. Most contact mouldings are made in the cold (room temperature) sometimes followed by post-curing. There may also be heat assisted contact moulding using gentle heat to speed up the process. Hand or roller pressure removes any trapped air while the resin is still wet. Plastics commonly used in this process are epoxies, polyesters and polyamides.

2.4.2 Spraying

Normally assisted by the use of an air spray gun incorporating a cutter that chops continuous roving to a controlled length before being blown into the mould simultaneously with the resin. Curing possibilities are similar as for contact moulding. The same resins as for hand lay-up are used on spraying lay-up.

2.4.3 Matched die moulding

There are two main reasons for developing this process. Firstly, sometimes it is necessary for both faces of the part to have a good finished surface, which is not possible using contact moulding or spray lay-up. Secondly, this method increases speed of production although with a greater investment in equipment and metal moulds. The real difference in the process is the type of material being moulded. Pre-forms from mat or roving are common, pre-preg forms can also be used and tailored fabrics or dough moulding compounds are also available. The process then becomes much like the compression moulding of any thermosetting plastic. Recommended plastic materials to be used on this process are alkyds, epoxies, phenolics, polyesters, polyamides and silicones.

2.4.4 Low pressure methods

The usual objective of these methods is to obtain good surfaces on both sides of the part. A single mould is used on which wet laying-up is frequently practised and on top of this is laid a smooth release film such as Cellophane. A flexible rubber bag is placed over this and air pressure up to 350 kPa is applied to give a reasonable moulding and relatively smooth surface. For this particular process the most popular materials are epoxies and polyesters.

2.4.5 Continuous methods

In these methods, mat is usually fed in one end of the system, impregnated and consolidated between the nip of rollers or a die. In automatic methods the material is then cured continuously in ovens. In partially automatic methods, it is cut up and taken away for batch curing. The material, which might be roving or strand as well as mat, is frequently pulled through the system and sometimes this process is called pultrusion. As before, epoxies and polyesters are the most popular materials on applications using this manufacturing process.

2.4.6 Confined flow methods

This term covers those processes where mat is confined between two mould surfaces and a resin is forced into the interstices by various means. One method consists in applying vacuum between the mould surfaces, which draws in the resin; another is applying pressure to resin in a pot by means of which it is forced in. This later process is also known as pressure impregnation and injection. The vacuum method is frequently called Marco-Vacuum method. Materials recommended for injection include alkyds, phenolics and silicones.

2.4.7 Casting techniques

Encapsulation may be practised with polyester resins and epoxies, either with or without fibrous fillers. Centrifugal casting may also be employed where round objects such as pipes can be formed. The mat is positioned inside a hollow mandrel and the assembly placed in an oven and rotated.

2.5 Manufacturability Analysis

The actual global marketing conditions of the manufacturing industry are demanding designers and manufacturers to bring products into market at competitive prices. To accomplish this goal they need to take the right decisions early in the design process where small changes in design account for an important portion of the final costs and are crucial to the success or failure of the product.

Integrating design and manufacturing seems to be an efficient way to reduce the product development cycle and consequently to achieve significant savings in the whole process of product development. Manufacturability assessment can be performed interactively during or after a preliminary design to make a product functionally acceptable and compatible with a selected manufacturing process (Chen, et al, 1995). Nevertheless, one of the main problems in performing manufacturability analysis of a new product is the deficiency of integration between design specifications and manufacturing process capabilities (Shah, et al, 1990).

It is difficult to get many interactions between design and manufacturing, as it is difficult to turn designers into manufacturing experts, therefore there is a need for expressing manufacturing expertise obtained from experts in the field and making it available in a feature-based manufacturability analysis system.

"*Manufacturability*" is a relative and subjective term based on the judgement on whether or not the manufacturing specifications agreed for the product are justified by its functions, performance and/or quality. Therefore, manufacturability can be defined as the quality of a design in terms of manufacturing feasibility and economics.

A reinforced plastic component is suitable for production if at least one process can be found so that the product design parameters do not violate any process constraint. Usually, evaluating manufacturability of a part model is not an easy task, which mostly involves several interrelated factors such as material properties, shape and size of the part, and capabilities and limitations of the manufacturing process required.

Detailed information of the product is not usually available in the early stages of design, and thus decisions are always made using qualitative information and designer judgement. As such decisions are not easy to make, expert knowledge is required to direct the evaluation. Traditionally, this evaluation relies on human experts, such as product designers and manufacturing engineers who are required to have a high standard of specific knowledge and expertise. This evaluation is a long and complex process, and since this expertise is not always available in house, then using expert systems to perform manufacturability analysis is a growing practice in the industry.

Software tools have had some successes in reducing the barriers between design and manufacturing. Manufacturability analysis systems are emerging as one of those tools allowing identification of potential manufacturing problems during the design phase and providing suggestions to designers on how to eliminate them. Systems already exist that can assess a design, generate process plans and detect potential problems in a design. Such systems are surveyed by Gupta, et al, (1997).

Several approaches had been used in manufacturability analysis, but most of them are intended for production planning of machined metal components. Although moderately successful, these systems have limitation in the type of geometric data they can process. Some of them are limited to a 2 1/2 dimensional geometry, while others deal with turning profiles. A second limitation of existing systems is their lack of initiative and solving capabilities, where detection of the problem is as far as most systems will go. Early detection of the problem is valuable, but a tool that could solve a proportion of the manufacturing problem early in the design stage would be beneficial.

The agent-driven approach of Jacquel and Salmon (2000) falls in the category of design by features and utilises a restricted set of form features which constraint the freedom of design. The system implements four criteria (presence, proximity, collision and access) related to the manufacturability of milling and drilling process of prismatic components.

Current KBS applications in solving manufacturing problems of plastic parts are relatively new and few, besides being mostly focused on plastic injection processes. Some researchers, however, have started to adopt KBS in capturing injection moulding part design features from CAD models, advising plastic material selection, automating the mould design process, developing design for manufacturability in mould design, etc. PLASSEX (Agrawal and Vasudevan, 1993) was developed to select plastic materials based on part requirements. IMDA (Borg and MacCallum, 1995) was developed for injection mould design, which requires part design details, such as 3-D geometrical profiles and dimensions as compulsory inputs to the system. Typically, these applications use a rule-based forward-chain method.

One of the primary goals of Concurrent Engineering (CE) is to build intelligent CAD systems by embedding manufacturing related information into CAD systems. In such intelligent systems, Design for Manufacture (DFM) is achieved by performing automated manufacturability analysis. Design errors, such as missing a corner radius, a high requirement for a surface finish or a wrong draft angle specification, which can go undetected during design stage, may prove to be costly during manufacturing stage. A systematic methodology for manufacturability analysis will help in building systems to identify these types of problems at the design stage, and provide the designer with the opportunity to repair them.

The main characteristics that differentiate one manufacturability analysis system from another include the kind of approach used, the measurement of manufacturability they use, and what level of automation they achieve.

2.5.1 Manufacturability analysis approaches

Basically there are two different orientations for analysing the manufacturability of a proposed design, they are direct or rule based approaches and indirect or plan-based approaches (Gupta, et al, 1997).

Rule based approaches are used to identify infeasible design attributes from direct inspection of the design description or geometry. This approach is useful in domains such as near-net shape manufacturing and moulding processes. However, it is less suitable for machining processes, where interactions among operations during the manufacturing process can make it difficult to determine the manufacturability of the design directly from the design description or geometry.

In plan-based approaches the first step is to prepare all possible manufacturing plans, and then modify sections of the plans in order to reduce their cost. Finally, choose the most promising plan.

2.5.2 Measure of manufacturability

The purpose of having a measurement of the manufacturability is to provide designers with a tool that allows them to judge the possible manufacturing difficulties involved in a proposed design. There are many different scales on which manufacturability can be expressed, but they can be classified into binary, qualitative and time-cost.

Binary measure is the most basic kind of manufacturability rating. It simply reports whether or not a given set of design attributes is manufacturable. It is also known as "Good Practice" rules violation and its main advantage is that makes the designer aware of deviations from accepted practice. It does not require any cost estimation. On the other hand, its disadvantages are related to the fact that rules are hard to collect and represent. Also, it does not provide any comparison between two designs that "pass" all the rules.

Qualitative measures assign grades to a particular design in terms of its manufacturability by a certain production process. For example, Ishii (1993) rated designs as 'poor', 'average', 'good', or 'excellent'. Sometimes such measures are hard to interpret and compare.

Time-cost measures consider the fact that all manufacturing operations have measurable time and cost, where the user can use them as a basis for a suitable manufacturability rating. To some extent designers can use target production time and cost as a reference point for comparing design options.

2.5.3 Level of automation

This characteristic involves the interaction between designer and system as well as the type of information provided to the designer as feedback. Some systems allow interaction using only a feature library available in the system (e.g. Jakiela and Papalambros, 1985) while in others it is possible to work directly from the solid model of the design (e.g. Yannoulakis et al, 1994).

Regarding feedback, some of the systems provide redesign suggestions to improve the actual design. Usually, those are suggestions to change parameters of various design features (e. g. Schmitz and Desa, 1994), but some systems present redesign suggestions as complete new objects (e. g. Hayes et al, 1989).

Since features are application dependent, then approaches to computer-aided manufacturability analysis are strongly influenced by the type of manufacturing processes they select to address.

2.6 Introduction to Neural Networks

Connectionism is a current focus of research in a diverse number of disciplines, among them artificial intelligence, physics, psychology, linguistics, biology and medicine. Connectionist systems represent a special kind of information processing which consist of many primitive cells (units, neurons or nodes) working in parallel and are connected via directed links (connections). The main processing principle of these cells is the distribution of activation patterns across the links similar to the basic mechanism of the human brain, where information processing is based on the transfer of activation from one group of neurons to the next group through synapses. Artificial Neural Networks (ANN) had been defined as mathematical models, which represent the biological process of a human brain (Raviwongse and Allada, 1997).

In these connectionist models, knowledge is usually distributed throughout the net and is stored in the structure of the topology and the weights of the links. Therefore, the net topology, node characteristics and training or learning rules specify the parameters of neural network models. The function of a neural network is determined by these parameters. The training or learning rules determines how the network will react when an unknown input is presented to it. Figure 2 shows a small network with three layers of units.

A neuron receives input stimuli from other neurons if they are connected to it or/and the external world. A neuron can have several inputs but has only one output. This output, however, can be routed to the input of several other neurons.

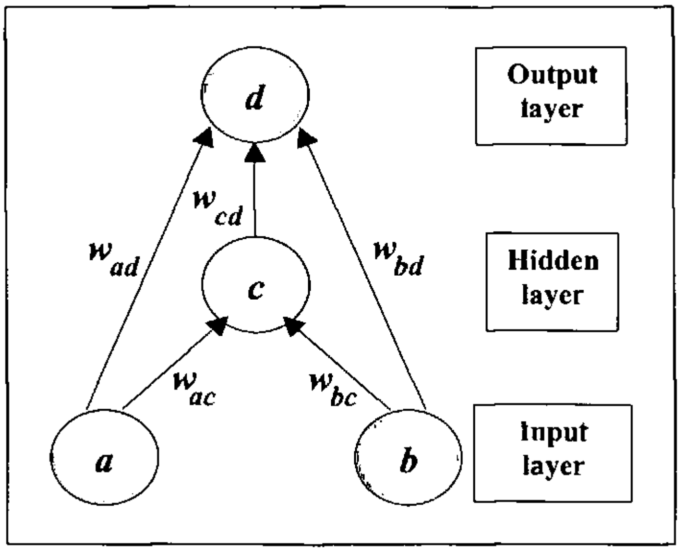


Figure 2. A small network with three layers of units and its weighted connections.

The output of a neuron depends on the input signals, weights of connections, threshold value and activation function, i.e. it computes the weighted sum of its inputs, subtracts its threshold from the sum and passes the result through its transfer function. The output of the neuron is the result obtained from the activation function.

2.6.1 Neurons and its activation functions

A neural network consists of neurons and directed weighted links between them, where each neuron receives a net (total) input that is computed from the weighted outputs of prior neurons with connections leading to this neuron. The network topology, or the architecture of the net, determines the inputs of each node. The node characteristics (threshold, transfer function and weights) determine the output of the node or neuron. The threshold or bias of the neuron determines where the activation function has its steepest ascent. Learning procedures, like back-propagation, change the bias of a neuron like a weight during training. The actual information processing within the units is modelled with the activation function and the output function. The activation function computes a new activation from the output of preceding neurons, usually multiplied by the weights connecting these predecessor neurons with the current neuron, the old activation of the neuron and its threshold. These functions may be different for each neuron in the network.

The general activation formula is:

$$a_j(t+1) = f_{act}(net_j(t), a_j(t), \theta_j) \quad [1]$$

Where:

$f_{act}()$ *is the activation function,*

$a_j(t+1)$ is the activation of neuron j in step $t+1$,

$net_j(t)$ is the net (total) input in neuron j in step t,

$a_j(t)$ is the activation of neuron j in step t, and

θ_j is the threshold or bias of neuron j.

The result of feeding a signal through two or more layers of linear processing elements are not different from what can be obtained using a single layer net. Therefore, a non-linear activation function is required in order to achieve the advantages of multi-layer nets compared with the limited capabilities of single-layer nets. The activation function (f_{act}) used in this research is known as logistic sigmoid function, which computes the network input simply by summing over all weighted activation coming from preceding neurons and then squashing the result with the following logistic function:

$$f_{act}(x) = \frac{1}{(1 + e^{-x})} \quad [2]$$

The new activation at time (t + 1) lies in the range [0,1]. The logistic sigmoid function can be scaled to have any range of values that is appropriate for a given problem, but the most common range is from –1 to 1, which is called bi-polar sigmoid, or between 0 and 1, which is called uni-polar sigmoid (Fausett, 1994).

The net input $net_j(t)$ is computed with:

$$net_j(t) = \sum_i w_{ij} o_i(t) \quad [3]$$

Where:

$o_i(t)$ is the output of neuron i in step t,

j is the index for some neuron in the network,

i is the index of some predecessor neuron of neuron j,

w_{ij} is the weight of the link from neuron i to neuron j, and

This yields the well-known logistic activation function as shown in the following formula (Diamantaras and Kung, 1996):

$$a_j(t+1) = \frac{1}{1 + e^{-(\sum_i w_{ij} o_i(t) - \theta_j)}} \qquad [4]$$

The output function (f_{out}) computes the output of every neuron from the current activation of this neuron. The output function is in most cases the identity function and it makes possible to process the activation before an output occurs. The general formula is:

$$o_j(t) = f_{out}(a_j(t)) \qquad [5]$$

Where:

$o_j(t)$ is the output of neuron j in step t, and

j is the index for all neurons in the network.

To compute the new activation values of the neurons, the simulator has to visit all of them in some sequential order. The update mode used in this research is known as topological order, which is an asynchronous mode. Using this update mode the kernel of the simulator sorts the neurons by their topology. This order corresponds to the natural propagation of activity from input to output. In pure feed-forward networks, such as the one used in this research, the input activation reaches the output especially fast with this update mode, because many neurons already have their final output which does not change later (Zell, et. al, 1994).

2.6.2 Learning in neural network

An important characteristic of neural networks that make neural nets preferable to other systems is its ability to tolerate 'noise' in the input data. The second characteristic, which lends them a degree of superiority over other systems, is their ability to learn by examples, (Wang and Mendel, 1992). Some types of neural nets can be trained to perform recognition tasks by repeatedly presenting input patterns to the net. The net adapts its weights as a function of its inputs, the computed result and the desired result, if one is provided. This process is called learning. If the desired output is given to the net, the learning is supervised. If not, the learning is unsupervised.

An important focus of neural network research is the question of how to adjust the weights of the links to get the desired system behaviour. This modification is very often based on the Hebbian rule, which states that a link between two neurons is strengthened if both neurons are active at the same time. The Hebbian rule in its general form is:

$$\Delta w_{ij} = g(a_j(t), t_j)\, h(o_i(t), w_{ij}) \qquad [6]$$

Where;

$g(\ )$ is the function depending on the activation of the neuron and the teaching input,

$a_j(t)$ is the activation of neuron j in step t,

t_j is the teaching input or desired output of neuron j,

$h(\ )$ is a function depending on the output of the preceding neuron and the current weight of the link from neuron i to neuron j,

$o_i(t)$ is the output of neuron j in step t, and

w_{ij} is the weight of the link from neuron i to neuron j.

Training a feed-forward neural network with the supervised learning algorithm consists of the following procedure:

- An input pattern is presented to the network. The input is then propagated forward in the net until activation reaches the output layer. This is called *forward propagation* phase.

- The output of the output layer is then compared with the teaching input. The error, i.e. the difference (delta) δ_j between the output o_j and the teaching input t_j of a target output neuron j, is then used together with the output o_i of the source neuron i to compute the necessary changes of the link w_{ij}. To compute the deltas of inner neurons (hidden layer), for which no teaching input is available, the deltas of the following layer, which are already computed, are used in a formula given below. In this way the errors (deltas) are propagated backward, so this phase is called *backward propagation* phase.

The most popular learning algorithm, which works in the manner described, is currently called back-propagation. In the back-propagation learning algorithm online training is usually significantly faster than batch training, especially in the case of large training sets with many similar training examples. In batch training methods the data X are collected and processed in a batch. Because of storage considerations batch methods are preferred when relatively few data are to be processed relatively few times, otherwise the computational requirements become extremely high. Online training also called adaptive methods is preferred when arbitrarily long or infinite sets of data are to be processed. Such methods require less memory for data storage, since intermediate matrices are not explicitly formed. In addition, adaptive methods with constant learning parameters, or learning parameters that do not tend to 0 when the number of neurones tend to be infinite, can track gradual changes in the optimal solution rather inexpensively compared to batch methods.

The back-propagation weight update rule, also called generalised delta-rule reads as follows:

$$\Delta w_{ij} = \eta \ \delta_j \ o_i \qquad [7]$$

$$\delta_j = f_j'(net_j)(t_j - o_j) \quad \textit{if neuron } j \textit{ is an output neuron}$$
$$\delta_j = f_j'(net_j)\sum_k \delta_k \, w_{jk} \quad \textit{if neuron } j \textit{ is a hidden neuron}$$

Where;

ΔW_{ij} is the change in the weight of the link from neuron i to neuron j,

η is the learning-factor which is a constant for each net,

δ_j is the error or difference between the real output and the teaching input of neuron j,

o_j is the output of neuron j, and

o_i is the output of neuron i.

One of the major advantages of neural networks is their ability to generalise. This means that a trained network could classify data from the same class as the learning data that it has never seen before. In real world applications developers normally have only a small part of all possible patterns for the generation of a neural net. To reach the best generalisation, the data set should be split into three parts:

- The *training set* is used to train a neural network. The error of this data set is minimised during training.
- The *validation set* is used to determine the performance of a neural network on patterns that are not trained during learning.
- A *test set* for finally checking the over all performance of a neural network.

2.6.3 Feature recognition using a neural network

The worthiness of a network lies in its inference or generalisation capabilities over unknown test cases. Connectionist learning procedures are suitable in domains with several graded features that collectively contribute to the solution of a problem.

To be useful in a neural net-based application, the definition of a feature must be in terms of some specific parameters or entities, which can be used as inputs to a net (Looney, 1993). As it was previously mentioned, a feature is a mathematical function of some topological and/or geometric variables. Topological variables include relationships between faces such as face adjacencies, common edge convexities, number of internal loops, etc. Geometric variables are related to dimensions, tolerances, vertex position, etc. Those parameters have to be available for extraction from the solid model database of the part on which feature recognition is being performed. The reason for such a restriction is that the neurons of a network perform very simple arithmetic operations only, and do not perform any logic operations explicitly.

According to Prabhakar and Henderson (1991), the major steps to be carried out in applying this technique for solving the feature-recognition problem can be seen as follows:

- Code the solid model in terms of certain essential parameters and characteristics according to the feature definition and using the geometric and topological characteristics of the solid model.

- Construct a suitable part representation such that it can be used as input in the neural network. Let's say, as matrix or vectors.

- Construct the networks, one for each feature type, and train the network for feature recognition.

- Feed the network, and

- Verify the learning process.

It is difficult to classify feature recognition methods into a clean taxonomy, because there is considerable overlap between the various techniques already being used, such as matching, entity growing and volume decomposition. An advantage of the feature recognition using neural network approach is that it can be application-specific, therefore, it allows for developing of our own recognition program for a reinforced plastics application.

It may be mentioned that human reasoning is somewhat fuzzy in nature. The utility of fuzzy sets lie in their ability to model the uncertain or ambiguous data so often encountered in real life. Hence, to enable a system to tackle real-life situations in a manner more like humans, one may incorporate the concept of fuzzy sets into neural network (Sankar and Sushmita, 1992).

2.6.4 Neural network architecture

Development of a successful pattern recognition system using neural networks requires a combination of careful research and planning, educated guesswork and outright trial-and-error approach.

The preferred network for most pattern recognition, a signal processing and similar applications is a multi-layered feed-forward network called a back-propagation network. Back-propagation is probably the best approach to use if the input array is reasonably small and if the patterns to be learned do not vary greatly in their size or position in the input array (Rumelhart et al, 1986).

Limitations of the back-propagation network include a long training time for large networks, a propensity not to train at all due to local minima in the error surface and limited ability to deal with input patterns that are not translational, rotational, and size invariant (Waibel et al, 1989). However, with proper conditions of the inputs, and by using recent improvements to the back propagation algorithm, these limitations can be overcome.

The main questions in designing the architecture and then training a multi-layer perceptron are listed below:

1. How many layers of neurons should be used?
2. How many input nodes should be used?
3. How many neurons should be used in the hidden layers?
4. How many neurons should be used in the output layer?
5. What should be the identifier vectors?
6. How to train the network?
7. How can we test to determine whether or not the network is properly trained?
8. How can we improve the learning process?
9. What should be the range of the weights?
10. What should be the range of the network inputs and outputs values?

Answers to these questions can be found in previous work developed by several authors. A résumé of practical approaches to answer each one of these questions is presented below.

Hornik (Hornik, et al, 1989) states that a hidden layer and an output of layer of neurons are sufficient, provided that there are enough neurons in the hidden layer.

The number N of input nodes must be the number N of features in the characteristic vectors, so that once a set of characteristics is chosen, their number N is fixed.

Answer to question number three is difficult. The number M of middle neurons is related to the number of linearly separable subclasses among the classes. Some authors discuss the number M of hidden neurons required (i.e. Huang and Huang, 1991, Kung and Hwang, 1988), others analyse the number Q of samples required (i.e. Mehrotra et al, 1991). But the truth is that there is a relationship between Q and M that determines whether or not a unique global sum-squared error solution exists, which suggest the following guideline: use $M = 2K$ for a small number K of classes ($2 < K < 8$) (Looney, 1996).

Answer to question four gives the number J of output neurons, which depends on the resolution required (the number K of classes) and gives the representation-encoding scheme to be used. It is possible to take $J = \log_2 K$ (from $K = 2^J$), which permits 2^J combinations of high and low (1 and 0) outputs of the J components (Hilera and Martinez, 1995).

With respect to question number five; the requirement here is to design a set of identifiers to be paired with the input characteristic vector. Any output must be in the range of the activation function [0,1] (uni-polar) and [-1,1] (bi-polar). The design goal is to separate the input vectors without error, therefore identifier vectors should build to be as different as possible from each other (Pattern Recognition, pr.html at cs-alb-pc3.massey.ac.nz, 1998).

There are multiple algorithms that can be used to train the network, so it is not possible to give a single answer to question number six. Some trial-and-error approaches may be required to find out which is the best algorithm for the current application and data set. It was decided to use standard back-propagation as the training function under supervised learning for the development of the present application.

Answer to question number seven involves using a training subset of the sample of exemplar pairs and two other disjointed test subsets that are to be used for validation and verification but not for training. Regarding that there are sufficiently many exemplars, we may select 25% of them at random to save for validation, another 15% to serve as final verification, and use the remaining for training as suggested by Lankalapalli (Lankalapalli, et al, 1997).

Answers to the remaining questions, eight to ten, are bound. Again, some trial-and-error approach may help to determine the best learning rate for particular network architectures. According to Looney's report, values for the rate of learning ranging from 0.2 to 0.3 are shown to be very effective in different applications (Looney, 1996). Regarding the range of weights, it is recommended that they must be kept between -1 and 1, because the inputs and outputs do not exceed 1 in magnitude and the activation functions squash the summed values to within unit magnitude.

There are many tools available in the market for the creation and development of artificial neural networks, such as Neural Networks, Mathlab Neural Network Toolbox, the Stuttgart Neural Network Simulator (SNNS), and others. SNNS software from the University of Stuttgart in Germany was used for the construction and training of the neural network to be used in this research. The main reasons for choosing this application are its flexibility and the familiarity of the user with this system. SNNS allows using a diversity of network architectures and several activation functions during the development of a particular network application. Furthermore, SNNS is a Windows 95 application, which is compatible with the requirements of the current application in terms of using low performance computers.

Chapter 3

3 CONCEPTUAL FRAMEWORK OF THE RESEARCH

This chapter will present the basic concepts used for the development of the FEBAMAPP system as presented in Figure 1. Firstly, those concepts regarding the CAD representational scheme and the structure of the file used as the input to the system. Secondly, the concepts involved in the design of reinforced plastics components, which will consider the limitations and capabilities of the materials and processes. Finally, it will be considered those concepts regarding the selection of manufacturing process.

3.1 CAD Representational Schemes

The use of a single representation of a component geometry in three-dimensional (3-D) space is the basis for downstream applications that involve interrogating the model to extract information for analysis and manufacture. The methods that have been developed for 3-D modelling involve the representation of geometry as a collection of lines and other curves (wire-frame), or of surfaces, or of solids in space.

The wire-frame scheme is relatively straightforward to use, and it is the most economical in terms of computer time and memory requirements, but it exhibits a number of serious deficiencies when used to model engineering objects. These include:

- Ambiguity in representation, and possible nonsense objects.
- Deficiencies in pictorial representation where silhouette edges of cylindrical objects may not normally be generated.
- Limited ability to calculate mechanical properties, or geometric intersections.

- Wire-frame geometry is of limited value as a basis for manufacture or other kind of analysis.

Many of the ambiguities of wire-frame models are overcome by using surface modelling. These are often constructed using a series of geometric entities, with each surface forming a single entity. Unfortunately, in surface models there is not information about connections between the different surfaces of the model, nor about which part of the model is solid.

Wire-frame and surface models are a satisfactory representation of the objects for many engineering purposes, but the increasing application of computers to engineering analysis, or to the generation of manufacturing information, means that an ideal representation should be as complete as possible.

Representation of solid models has been the subject of research over the last twenty years or so, and continues to be a major theme for study, as the objectives have by no means been achieved. Many methods have been proposed for solid modelling, of which none yet meets all the requirements in full, but two have been partially successful, and have come to dominate the development of practical and commercial systems. These are the Boundary Representation (B-Rep) and the Constructive Solid Geometry (CSG).

As an example, the feature recognition systems developed by Joshi and Chang (1990), Prabhakar and Henderson (1992), and Laakko and Mantylla (1993) are based on B-Rep scheme. The feature recognition systems developed by Lee and Fu (1987), Kim and Roe (1992) are based on a CSG representational scheme. Yamaguchi et al. (1984) used an octree approach to determine the rough machining paths. Allada and Anand (1992) have identified the various manufacturing applications of octree/quadtree models and discussed the suitability of a hybrid octree/B-Rep structure over the hybrid B-Rep/CSG structure for feature-based design applications.

3.1.1 Boundary Representation (B-Rep)

The most common CAD representational scheme for feature recognition systems is B-Rep for the following reasons:

- Contains information in an 'evaluated' form, meaning that the information regarding geometry and topology of the part is ready to use if further analysis is required.

- The information present in B-Rep is independent of the designer's creation sequence of the part model.

- B-Rep scheme of a part model is 'unique'.

When information is added about connectivity relationship between surfaces and, in addition, the solid side of any surface in the model is identified, then this forms the elements of the B-Rep scheme. In a B-Rep, there are three components of a surface, named face, edge and vertex.

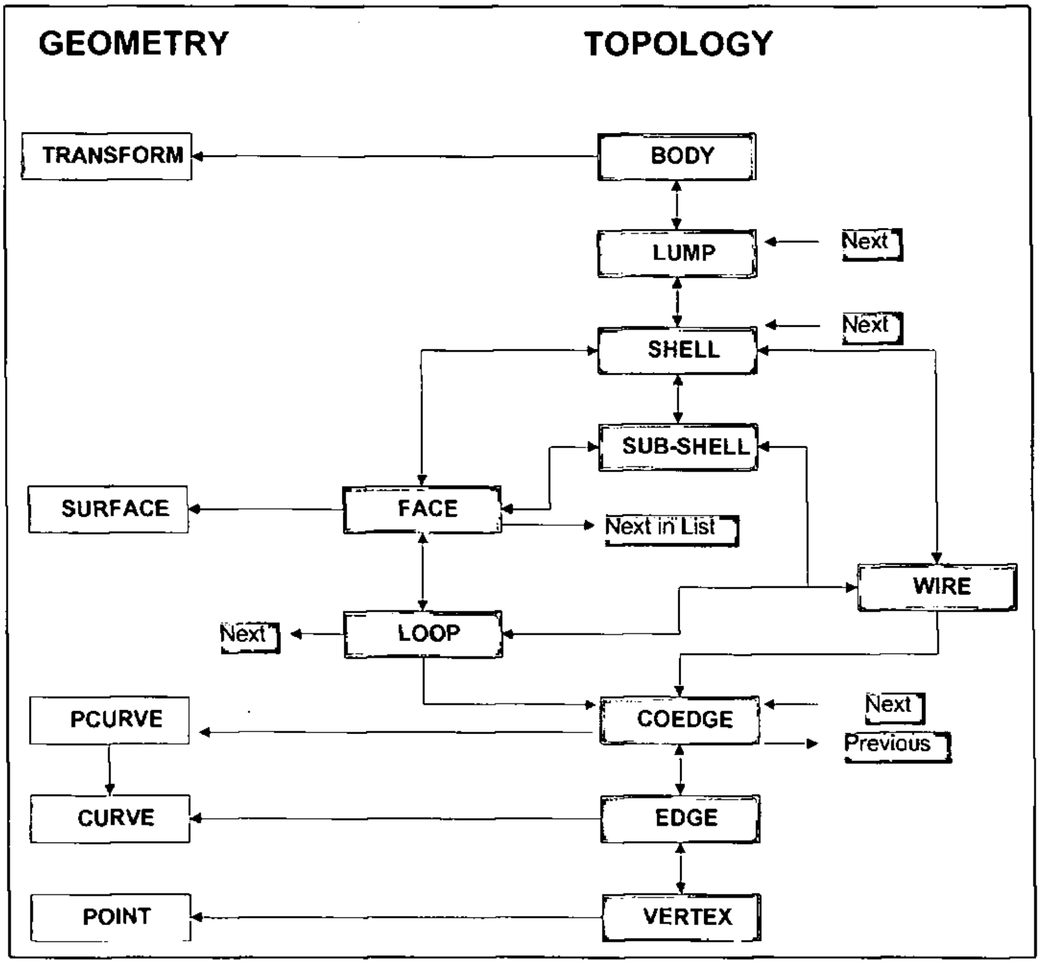


Figure 3. Structure of a B-Rep scheme of a solid object.

The information associated with the surface components consists of relationships between adjacent components, dimensions and location of them. There are three types of geometric entities and nine classes of topological relationship (Choi et al. 1984). However, it is not necessary to store all the geometric definitions and topological relationships since some can be derived from others. In general, the question of which kind of information should be stored depends on the application purposes. Figure 3 shows the scheme corresponding to a B-Rep model.

Real systems also include methods for checking the topological consistency of models such as extra or missing surfaces or connections. Topological consistency is in part achieved by using a data structure in which faces or surfaces are linked (with the appropriated adjacency relationships) with their bounding edges, which are in turn linked to their bounding vertices in a uniform structure.

Boundary models store information about the faces and edges of a model explicitly in what is known as an evaluated form. This allows that on certain applications, information of the model can be extracted directly from the data structure. A disadvantage of this representation is that the amount of data stored is relatively large, and therefore B-Rep models tend to require large data files.

3.1.2 Constructive Solid Geometry (CSG)

In this method, the models are constructed as a combination of simple solid primitives, such as cubes, cylinders, spheres, cones and the like. The resulting models are often compact, but may be stored in an unevaluated form in which the edges and faces that result from the combination of the primitives has to be computed when required with the attendant performance penalty (McMahon and Browne, 1993).

At first glance, one might find the CSG scheme to be better suited for automatic feature recognition systems. However, the CSG representational scheme has many problems for the automatic feature recognition applications. The CSG tree contains information in an 'unevaluated' form, i.e. the geometry and topology of the part is not readily available. In addition, the CSG tree representation is 'non-unique', which means that a part can be constructed using several different ways and each one of them will have a different database structure for the same object.

The method of constructing CSG models is such that quite complex shapes may be developed relatively quickly, but only within the limitations of the set of primitives available within the system. Many features found on engineering components such as fillet blends, or draft to allow the component to be withdrawn from the mould or die, may be difficult or time-consuming to produce using CSG techniques. Besides, CSG in general is not a unique representation of an object and that represents a major obstacle to be used on automatic feature recognition and manufacturability analysis applications.

3.1.3 Dual representation

The different techniques used in CSG and B-rep modelling present distinct advantages and disadvantages. CSG models tend to be more robust, let's say they are less inclined to numerical or computational errors or limitations, and have advantages where a membership test is required. B-rep models tend to offer improved performance in display generation, and more flexibility in the forms that may be modelled. From the previous rationale some systems have until recently been hybrids of the two techniques.

There is also an increasing tendency for commercial modelling systems to combine solid modelling techniques with surface and wire-frame representation in a more or less unified framework, from which the user may choose the most appropriated technique for a given problem.

3.1.4 Octree and quadtree models

Octree models are volumetric models that provide a hierarchical decomposition of the space of interest. The object of interest is enclosed in a cube known as the root node of the octree. If any node is completely occupied it is labelled as a black node, if the node is completely empty it is labelled as a white node. White and black nodes are terminal leaf nodes and are not divided any further. If a node is partially occupied it is labelled as a grey node and is recursively subdivided into eight octants until a black or white terminal node is found. Since it is cumbersome to represent an octree in a tree format, linear octree representations have been proposed. Most linear structures denote the path address of the white or the black nodes.

The two dimensional version of the octree is known as quadtree. For a quadtree the object lies within a 2n x 2n region, where n is the resolution parameter. The two dimensional space of interest is broken up into quadrants which are labelled black, white or grey.

Some of the advantages of octree and quadtree models include ease of boolean set operations, computation of volume and mass properties, and ease of object rendering. One of the drawbacks is their lack of accuracy in modelling objects. Since hierarchical cubes or squares represent the objects, exact representation of the boundary is not possible.

3.2 Design Characteristics of Reinforced Plastic Components

Characterising the manufacturing processes for design requires an understanding of the influence and interactions of design and process variables on the final quality of the part being designed. The variables to consider are often properties of the materials selected, of the geometry of the part, of the equipment and tooling and of the manufacturing environment conditions. Under these particular set of conditions, a primary problem to be solved in developing a KBS of manufacturability analysis is to provide manufacturing knowledge to the designer in a useful form (Padmanabhan and Finger, 1995).

Design of a reinforced plastic (RP) product can be considered from two different points of view. First, customers require a product of functional and aesthetic value and prefer freedom in design shape. Second, the manufacturer who will make the object has to consider design from the manufacturing point of view regarding materials, tools, processes, production rates, and some other factors which affect product quality and costs.

The design of successful plastic products requires a lot of judgement based on experience, and it is very difficult, even for the most experienced designer to be capable of developing a new product all by themselves. Certainly those designers who are new to the reinforced plastic field, or plastics in general, must take advantage of the experience, judgement and knowledge of others who work constantly with some aspects of the plastic product development field.

There are at least three major fields of expertise involved in the development of RP components. Those fields are usually known as product design, materials development or materials selection and manufacturing engineering. The team these parties constitute is often informal and individuals may be employed by different organisations or they may be in the same company. A relationship between each other and the product is absolutely necessary in pursuing the development of a successful new RP product (AVENPLAR, 1996).

Most of the time, getting this team together to work on a specific project is a real problem and expert systems (ES) are in fact helping to overcome these difficulties. Among the advantages of using ES are the facts that they make available expertise otherwise not available in plant. They also make available different techniques, material's data, and further information regarding product, materials and processes, therefore making it easier to support the designers' work all the way in a new product development process.

There are some design recommendations that are particular for each manufacturing process, but also there are some general points that should be considered at design stage for any particular RP component. The following list includes the most important design considerations of reinforced plastic parts (Marquez and Criollo, 1997):

- Magnitude and duration of forces to be applied to the component.
- Seek for high concentration of forces.
- Aim for the simplest shape and form.
- Keep wall thickness as uniform as possible, and avoid drastic changes on it.
- Choose wall thickness appropriate to the process and type of material to be used.
- Avoid internal and external undercuts, as they are high-cost features.
- Use appropriate draft angles on walls, pockets, ribs and bosses.
- Use appropriate radii in all edges and corners.
- Avoid the use of large flat areas.
- Choose holes and pockets of suitable dimensions and location.
- Provide inserts with proper anchorage and proper location.
- Allow clearances for easy tool-reach.

- Keep tolerances as large as possible.
- Keep in mind any manufacturing process limitations.

As it can be seen, there are several variables to be considered during the design stage of a RP component, the most important being wall thickness, fillets, draft angles, shrinkage, holes, tool-gap, and inserts. The manufacturability analysis proposed in this research will give special attention to those variables, keeping in mind the most popular RP manufacturing process.

3.2.1 Wall thickness

The wall thickness is obviously an important factor in designing RP products and should be considered carefully. Thickness will not only depend on composition ratio (resin/reinforcement) of the reinforced product but also on the shape, strength and some other required design factors.

The main reason designers are tempted to increase wall thickness is to try to improve the component's strength and sometimes they forget that there are different approaches to solve this problem. The first way of increasing rigidity and strength of thin-walled objects is to corrugate the surface as it is extensively used in metal-sheet work. The second method is to introduce ribs at various points and the third is to increase the thickness at any desired point. But all of those methods have some design considerations that must be analysed before choosing between them.

In any case it is recommended that the thickness of a component be calculated on the basis of the maximum load it should support according to the following equations.

$$S = P / A \qquad [8]$$

$$A = t * w \qquad [9]$$

$$t = P / (S \times w) \qquad [10]$$

Where;

S is the allowable stress for the material,

P is the actual load applied,

A is the area supporting the load,

t is thickness of the part, and

w is the width of the section supporting the load.

In general, plastic components should be designed to have uniform wall thickness and a choice of a nominal value is a compromise, which depends on the plastic material, the reinforcement conditions and the manufacturing process to be used. In many designed parts, one or more structural requirements are mandatory and have, as a result, a profound implication on the wall thickness of the component.

Useful factors of safety recommended when designing with RP are given in Table 1.

Table 1. Recommended factors of safety.

LOAD TYPE	SAFETY FACTOR
Static short term loads	2
Static long term loads	4
Variable loads	4
Repeated loads	5
Fatigue or reversing loads	5
Impact loads	10

Source: Reinforced Plastics Handbook. John Murphy. 1994.

Proper distribution of stress and most effective use of material can be achieved by adjustment of the slope, contours, and shape of the part. Attention should be given to those aspects before thinking about increasing the wall thickness of the part. Indeed, adjustments of wall thickness as a means of coping with such problems is often not feasible for manufacturing and costs reasons, because heavy sections cannot be properly moulded and also require larger moulding and curing times.

The designer must also consider the implications of the manufacturing process on the choice of appropriate part wall thickness, and since the manufacturing process depends on the material to be used, then wall thickness will depend, besides the stresses, mainly in the chosen material. Table 2, contains suggested wall thickness for the most popular plastics used in RP manufacturing processes.

Table 2. Suggested wall thickness for fibre reinforced plastics.

	Minimum thickness		Average thickness		Maximum thickness	
Thermosetting materials	**(inches)**	**(mm)**	**(inches)**	**(mm)**	**(inches)**	**(mm)**
Alkyd	0.040	1.000	0.125	3.20	0.500	12.70
Epoxy glass	0.030	0.750	0.125	3.20	1.000	25.40
Phenolic	0.030	0.750	0.093	2.35	0.750	19.00
Silicon glass	0.050	1.250	0.125	3.20	0.250	6.35
Polyester	*0.040*	*1.000*	*0.070*	*1.80*	*1.000*	*25.40*
Thermoplastic materials (*)	**(inches)**	**(mm)**	**(inches)**	**(mm)**	**(inches)**	**(mm)**
ABS	0.030	0.750	0.090	2.30	0.125	3.20
Nylons	0.015	0.375	0.062	1.60	0.125	3.20
Acetal	0.015	0.375	0.062	1.60	0.125	3.20
Polyethylene	0.035	0.885	0.062	1.60	0.250	6.35
Polypropylene	0.025	0.635	0.080	2.05	0.300	7.60
Polystyrene	0.030	0.750	0.062	1.60	0.250	6.35
PVC	0.040	1.000	0.093	2.35	0.375	9.50
Polyurethane	0.025	0.635	0.500	12.70	1.500	38.06

(*) Mostly used for injection process.
Source: Design and Manufacture of Plastic Parts.
R.L.E. Brown. 1980.

3.2.2 Fillets

The use of adequate radii reduces stress concentration and results in stronger moulded products. Sharp edges should be avoided wherever possible. Not only are they a source of weakness, but they do not mould very well in the sense that rounded corners permit more uniform, unstressed flow of the plastic into moulds. Suggested minimum radii for some of the RP processes available are given in Table 3.

Some other authors recommend radii as a function of the thickness (T) of the part. A minimum of 1/3 of T, but interior radii less than 4 mm will not be recommended for most processes and materials. Preferred interior radii are ½ T, and equal wall thickness should be maintained between the inside and outside of the part at the corner section.

Table 3. Recommended minimum radii according to GRP process to be used.

PROCESS	RADII / (Inches)	RADII / (mm)
Hand laying-up	0.25	6.40
Spraying	0.25	6.40
Pressure bag	0.50	12.50
Filament winding	0.125	3.20
Hot Press	0.030	0.75
Cold Press	0.125	3.20

Source: Reinforced Plastics Handbook.
John Murphy. 1994

3.2.3 Draft angles

Table 4 gives some details about minimum draft angles to be used accordingly to selected materials.

Table 4. Shrinkage values and minimum draft angles recommended for particular materials.

Thermosetting materials	Draft angles [grades]	Shrinkage [%]
Alkyd	0.5 – 1.0	0.3 - 0.6
Epoxy glass	0.5 – 1.0	0. 2 - 0. 8
Phenolic	0.5 – 1.0	0.1 - 0. 5
Silicon glass	0.5 – 1.5	0.1 - 0.5
Polyester	0.5 – 2.0	0.5 – 2.5
Thermoplastic materials (*)		
ABS	1.0 – 2.0	0.1 - 0.7
Nylons	0.5 – 1.5	0.8 – 1.2
Acetal	0.5 – 1.0	2.0 – 3.0
Polyethylene	0.25 – 2.0	3.0 - 4.0
Polypropylene	0.25 – 1.5	1.5 – 2.5
Polystyrene	0.25 – 1.5	0. 1 - 0. 5
PVC	0.5 – 1.0	0.1 - 0.8
Polyurethane	0.25 – 1.5	0.5 – 1.0

(*) Mostly used for injection process.
Source: Design and Manufacture of Plastic Parts.
R.L.E. Brown. 1980

As in any other moulding process it is necessary to have a slight draft angle on vertical surfaces to facilitate extraction from the moulds. In general, walls, ribs, slots and pockets should have a minimum taper or draft angle of 1°. Filament winding process requires a 2-3° and for processes using a pressure bag 5° should be allowed. This is a most important provision and in large objects in particular there can be great difficulty in mould extraction if inappropriate draft angle is used.

Regarding the draft angle, the depth of vertical walls affects it, and this angle can be defined accordingly to Table 5 for some of the available RP processes and as function of the wall depth.

Table 5. Recommended draft angle for vertical walls according to several RP processes. [Angle in degrees]

	WALL DEPTH [mm]				
PROCESS	**0 - 25**	**20 - 50**	**40 - 200**	**150 - 500**	**500 - more**
Hand laying-up	1	2	3	5	7
Spraying	1	3	5	8	10
Pressure bag	5	6	8	10	12
Hot Press	1	1	1	2	2
Cold Press	1	2	2	3	5

Source: Reinforced Plastics Handbook.
John Murphy. 1994

3.2.4 Shrinkage and tolerances

Each plastic has a characteristic shrinkage or contraction that take place after the part has been moulded. Shrinkage can take place to the extent of 10% in some compositions although it can be reduced if some design and manufacturing details are considered.

Among the factors that can be mentioned which affect shrinkage are the amounts of preheat, curing temperature, pressure, time of moulding, etc. In addition to those factors the material and shape used also affect the shrinkage, but these two last factors are under the designer's control. In many cases the reinforcing fibre prevents shrinkage in the direction or directions in which they are aligned and therefore shrinkage mostly take place in the thickness of the part. Similarly, distortion is likely to occur on thin objects of large area unless suitably ribbed and allowance is made for it. Table 4 presents typical shrinkage values for common plastic materials used in RP manufacture.

Shrinkage is often used as an anchoring medium for metallic inserts as long as a suitable area is made available. Also, shrinkage is the main cause of convexity on large plain surfaces, which can be avoided by providing ribs in thc back of the plain surfaces. Tolerances have to be provided considering the shrinkage characteristics of used materials and design features.

3.2.5 Holes

Moulded holes commonly include holes classed as blind-hole, through-hole and step-hole. Figure 4 shows gcometrical details of these holes type.

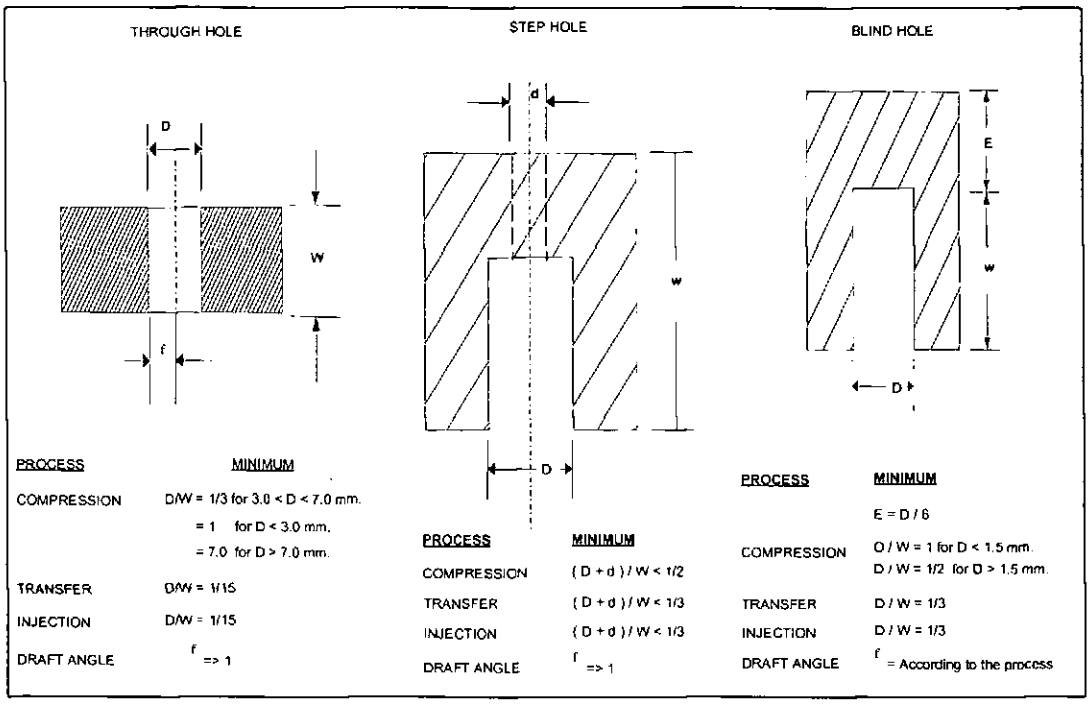


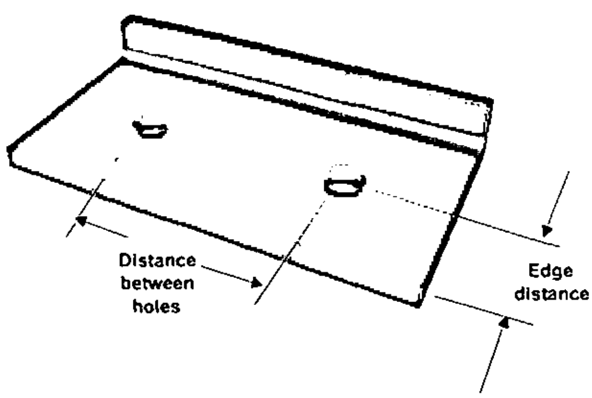
Figure 4. Moulded hole types and suggested dimensions.

Through-holes are preferred for injection and transfer moulding from a manufacturing point of view since the mould pins, which form the holes, can often be supported in both halves of thc mould. Blind-holes also known as circular pockets are formed by a core pin, which is supported only at one end. Moulded holes non-parallel to the draw direction requires complicated moulds, which require more direct labour than parallel holes. Holes entering the sides of the part should therefore be avoided and consideration for substitution using slots should be given to the design. If production rate of the part is low, it may be more economical to drill a side hole than to mould it. On the other hand, even for matched die processes, holes smaller than 1.50 mm. [1/16"] diameter should be drilled after the part is completely cured.

Location of the holes is also important and some consideration should be made regarding distances from the edges of the part and any other particular feature that can be affected by the location of holes. Another consideration should be made in reference to the distance between holes. Table 6 contains recommended distances to be used on location of holes.

Table 6. Recommended hole location.

Hole diameter		Minimum distance from edge		Minimum distance between holes	
[inches]	[mm]	[inches]	[mm]	[inches]	[mm]
0.062	1.50	0.093	2.40	0.140	3.55
0.093	2.40	0.109	2.80	0.187	4.75
0.125	3.20	0.156	3.95	0.250	6.35
0.187	4.75	0.218	5.55	0.312	7.90
0.250	6.35	0.250	6.35	0.437	11.10
0.312	7.90	0.312	7.90	0.562	14.25
0.375	9.55	0.343	8.70	0.875	22.25
0.500	12.50	0.437	11.10	0.875	22.25



Source: Design and Manufacture of Plastic Parts. R.L.E. Brown. 1980

3.2.6 Inserts

Inserts are used in parts requiring frequent assembly and disassembly operations, where strength is also required, or where there are particular requirements that can only be achieved using an insert. In general there is no difficulty in incorporating inserts. Shrinkage is such that mechanical locking is enough in most cases. It is, however, always recommended to use an epoxy adhesive as well. There must be sufficient material to surround and hold the insert without fear of cracking and this can be achieved by increasing thickness at the required point, particularly in the form of a bossing surface.

Usually, moulded-in inserts require accurate fits and location in the mould in order to avoid subsequent assembly problems. For these reasons moulded-in inserts, particularly threaded inserts should be used only if there are no other alternatives.

3.2.7 Tool-Gap

There is not a single recommendation regarding tool-gap but some guidelines can be followed for each process. For instance, tool-gap in open moulding processes are related to the tool size and ultimately to the material used. Mainly it should give enough room for laying and rolling tasks. Recommended value for a minimum tool-gap in open-moulding processes of hand and spray lay-up is 13 mm. Other processes such as pressure bag require greater tool-gap setting a minimum value in 25 mm.

In close moulding processes the reinforcement, resin characteristics and the use of pressure assistance to fill the mould limit tool-gap, make it impossible to give a single suggestion for this variable value.

3.3 Manufacturing Process Selection

The choice of a suitable process for a particular application will completely rely on the characteristics of the object to be produced. The first choice is between open or closed mould techniques, where any object requiring a smooth finish on both sides will be made in closed moulds. Whether the object needs to be smooth on both sides is a decision of the designer based on the functionality and/or appearance required. Also, in general, open moulding is cheaper than closed moulding and costs will have a considerable weight in the selection of the most adequate process for a particular application.

Even though appearance is a major factor in making the choice, selecting an RP process is highly related to some aspects of design since this will so closely affect the process and the materials selection for a particular product. We must think that design and manufacture are inseparable tasks. Selecting an RP process can be seen as part of the whole product development process, for instance if some broad idea from the market situation of the product's nature in terms of size, shape, and production rate is available, then narrowing the options for a particular manufacturing process is possible.

Very large objects, or objects which there will be only a few of, are recommended to be manufactured by open moulding techniques, usually contact moulding or spraying. Matched metal die moulding would be used for large production runs of smaller objects, while intermediate runs would be possible by a low-pressure method.

In general terms, the cheapest process which is consistent with the finish required, the size of the object and the production rate are the most important aspects to be considered in selecting the most appropriated RP processing for a particular design. It may be thought that its diversity of processes, perhaps making it difficult to select them in some cases, is a weakness, but in fact this is one of the strengths of RP, since almost anything can be made from it at the lowest possible cost.

From this product's initial information the relationships between candidate materials and a short list of suitable processes can then be considered. At this stage, designers can probably focus upon one or two materials in conjunction with one, or perhaps two, manufacturing processes. In comparing processes, by using published data describing the properties of plastics and reinforcements, special attention must be given to the fact that this data has been derived from short-term tests (Dreger, 1974). Therefore, it is good advice to seek results that most closely resemble the in-service conditions of the intended design.

Mould cost, however, is directly associated with the complexity of the product design. Manufacturing engineers should advise product designers if any possibility exists of lowering the tooling cost by removing some complicated and expensive mould features. Selection of mould material will be influenced by the number of parts to be produced, with large production runs requiring more expensive mould materials.

A final phase in selecting an RP process is to consider the economics. For many project managers, cost may be the most important single factor in selecting a suitable material-process combination for the composite product they want to produce. The CAD/CAM/CAE/CIM systems are fundamental for cost-effective, large-scale production, where in addition to developing and producing superior quality reinforced parts; these systems may reduce material handling, inventory and maximise utilisation of equipment and labour time.

Cost is often based on the production method and the number of items to be produced. Some processes may require a special atmosphere or protection for workers. On the other hand, some materials may be more expensive because it is more difficult to machine, fabrieate or finish. Furthermore, it is obvious that equipment and tooling costs will depend on part size, performance needs and complexity of design. Table 7 gives a comparison of RP processing and economic factors that may be useful in selecting a suitable process for a particular application or design.

Table 7. Economic factors associated with different RP processes.

PROCESS	Economic Minimum	Production Rate	Equipment Cost	Tooling Cost
Autoclave	100-1000	Low	High	Low
Bag moulding	100-1000	Low	Low	Low
Casting processes	100-1000	Low-high	Low	Low
Compression moulding	1000-10000	High	Low-high	Low-high
Filament winding	100-1000	Low-high	Low-high	Low-high
Lay-up	100-1000	Low	Low	Low
Spray-up	250-6000	Low	Low-medium	Low
Matched die	1000-10000	High	High	High
Press moulding	100-1000	High	Low-high	Low
Pultrusion	1000-10000	High	High	High
Transfer moulding	1000-10000	High	High	high

Source: Process Selection: From Design to Manufacture.
K. G. Swift and J. D. Booker. 1997.

Chapter 4

4 FEATURE RECOGNITION

4.1 The Recognition Process

Figure 5 illustrates sub-populations S1,..., S4 of a population 'P' of non-identical objects, along with the processing that recognises a sample object. An object's attributes are sensed or measured to yield a pattern vector that is transformed into a reduced set of features, and the object is recognised from its features by the recogniser.

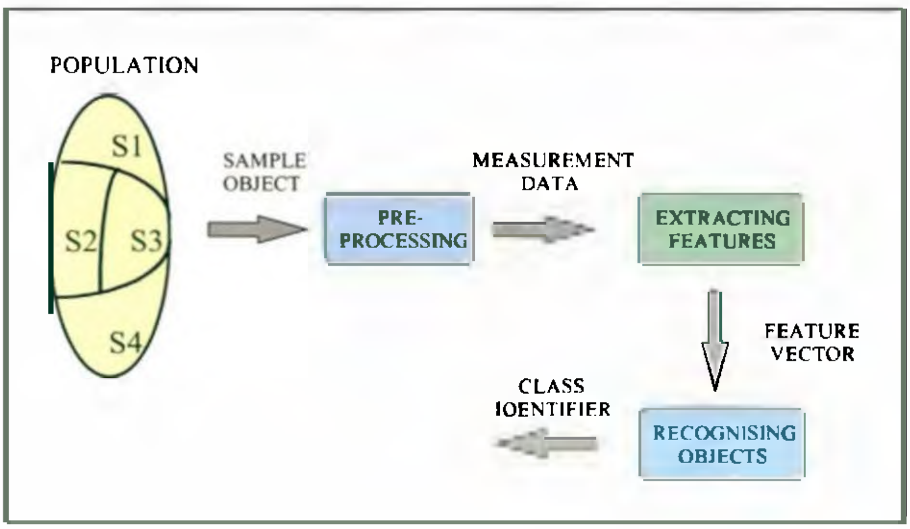


Figure 5. The recognition/classification process.

A pattern recogniser is a system to which a feature vector is given as input. This operates on the feature vector to produce an output that is the unique identifier (name, number, code-word, vector, string, etc.) associated with the class to which the object belongs (Looney, 1997).

An automated pattern recognition system is an operational system that minimally contains an input subsystem that accepts sample pattern vectors, and a decision-maker subsystem that decides the classes to which an input pattern vector belongs. If it also classifies, then it has a learning mode in which it learns a set of classes of the population from a sample of pattern vectors; that is, it partitions the population into the sub-populations that are the classes.

Feature extraction is the stage where the system converts an unprepared pattern into a feature vector. This stage is very important since it is in charge of reducing data redundancy in the pattern used. For a given population P of objects, an attribute is a variable *m* that takes on a real measured value. A feature is either an attribute or a function of one or more attributes. Features must be observable, in that they can either be measured, obtained as a function of measured variables, or estimated from measured values of correlated variables.

In general, a pattern vector of attributes is converted to a feature vector of lower dimension that contains all of the essential information of the pattern. Feature vectors from the same class, however, are also different. Typically, the differences come from three sources: noise, bias or system error, and natural variation between objects within the same classes due to unknown variations of operators that create the objects (Zulkifli and Meeran, 1999).

In the classification stage it is assigned the feature vector to an appropriated class, pattern space or feature space must be partitioned through a training process. The system is trained using a finite set of patterns called the training set. If the correct classification for these patterns is known then this is supervised learning, otherwise it is unsupervised learning. The performance of the system is evaluated using a different set of patterns known as the test set.

The pre-processing stage plays a fundamental role in the systems overall performance and for this reason we will dedicate a special session to this sub-system.

4.2 Data Pre-Processing

A feature recogniser can be considered as a tool that generates descriptions of features by analysing or transforming the solid model data structure of an object. However, the feature recogniser cannot read data directly from a solid model database and that is the reason a pre-processing of the solid data is required.

In the approach of using neural network as recogniser of features, a suitable format for the input data is necessary in the form of vector or matrix. The following sections will describe some of the concepts used in this research during the pre-processing algorithm of the solid's topological and geometrical data, such that it can be used as neural network input.

4.2.1 Concept of face graph

An object in a B-rep data structure consists of a set of faces and each face has neighbouring faces. In order to understand the relationship between each face and the other faces of the model, and using the concept of Face Graph introduced by Hwang (1991), it is possible to represent a 3-D object as a 2-D face set as shown in Figure 6. The 2-D face set is based on face 1 (f1) and it is assumed that each face in an object has similar structure.

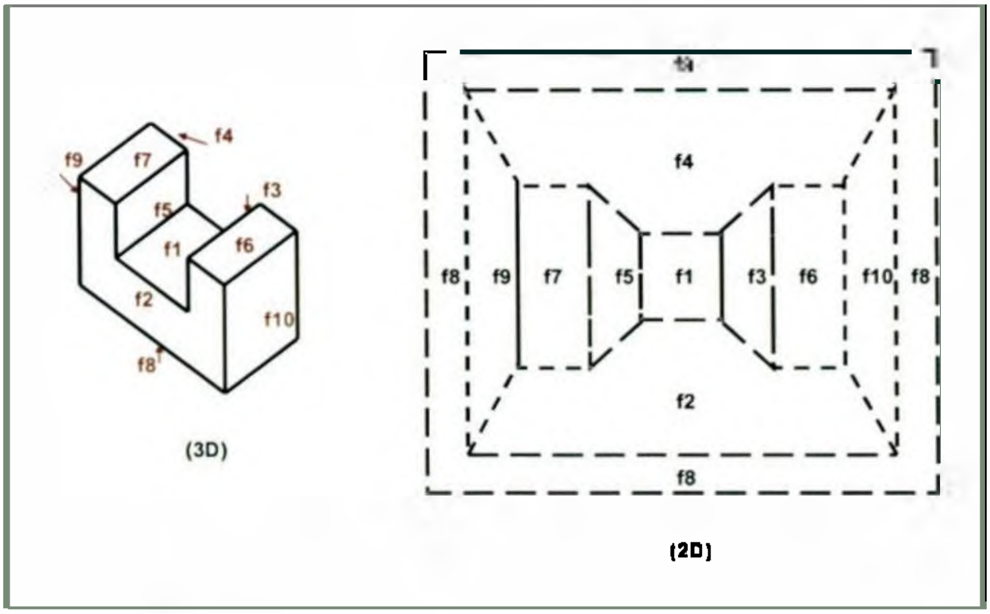


Figure 6. 2-D face set representation of a 3-D object.

The original concept was introduced in order to represent features in a suitable way for neural network input, but a modified face score value assignation is used in this research. The reason supporting this modification is based on the presence of fillets that give origin to vertices with four (4) edges and four (4) adjacent faces instead of three (3) edges and three (3) faces as considered by the former author. Furthermore, with the presence of fillets, any particular face with four edges will have as minimum eight surrounding faces instead of four, as shown in Figure 7.

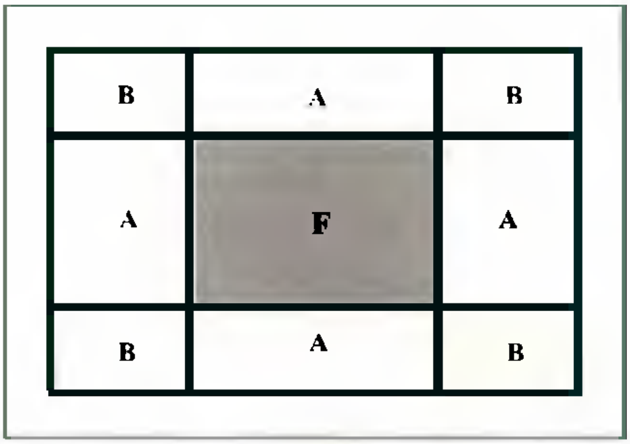


Figure 7. A 2D representation of a 3D solid with fillets.
'Sharing-Edge' (A - F) and 'Sharing-Vertex' (B – F) relationship between adjacent faces.

Two different kinds of relationship between adjacent faces should be described as a foundation for the feature definition used in this research. In first place, 'Sharing-Edge' relationship that occurs between two adjacent faces sharing an edge of the object (A – F) and in second place, 'Sharing-Vertex' relationship, which occurs between two adjacent faces that share only a vertex of the object (B – F), also represented in Figure 7.

If a particular value, representing face characteristics, is assigned to each face in the object and those values are represented as vectors then it is possible to say that a Face Graph (FG) of the part has been created as shown in Figure 8. In order to assign weighted values to each face it is necessary at this point to introduce the concept of convexity and concavity to be used in this research.

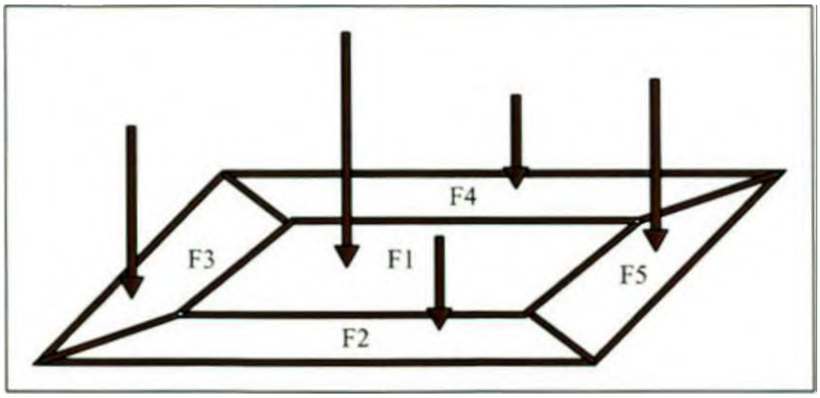


Figure 8. Face graph (FG).

4.2.2 Concept of convexity and concavity

A region is convex if, for each pair of points in the region border, the straight line between those points stays in the region. This definition can be extended to faces in a B-rep solid model as shown in Figure 9. If we say that one straight line between two points in the surface of the face stays inside the body of the solid model, then the face is convex otherwise it is concave. For convention in this research a planar face will always be considered as convex.

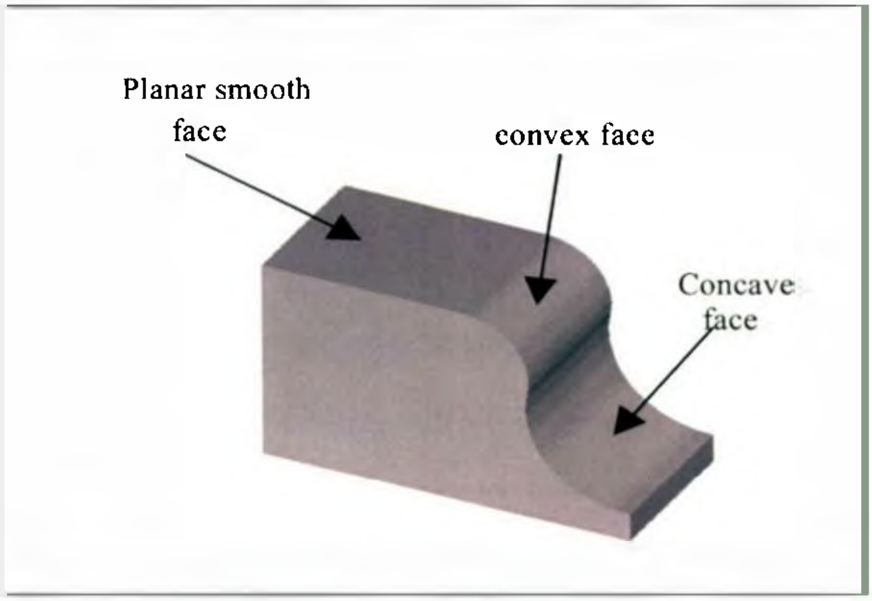


Figure 9. Face classification.

According to Chuang and Henderson (1990), a point on a B-rep element can be classified as convex or concave by defining an infinitesimally small spherical neighbourhood with the point at its centre. If the spherical neighbourhood is filled by more than half with solid material, then the point neighbourhood is concave. If the sphere is half filled with solid means that the neighbourhood is smooth, else it is convex.

Classification of an edge can be done on the basis of the angle between the faces sharing the edge, which can be classified as smooth, convex or concave. A vertex, based on the types of edges sharing the vertex, can be classified as concave or convex. A convex vertex means more convex edges than concave edges sharing it. An illustration of this is shown in Figure 10.

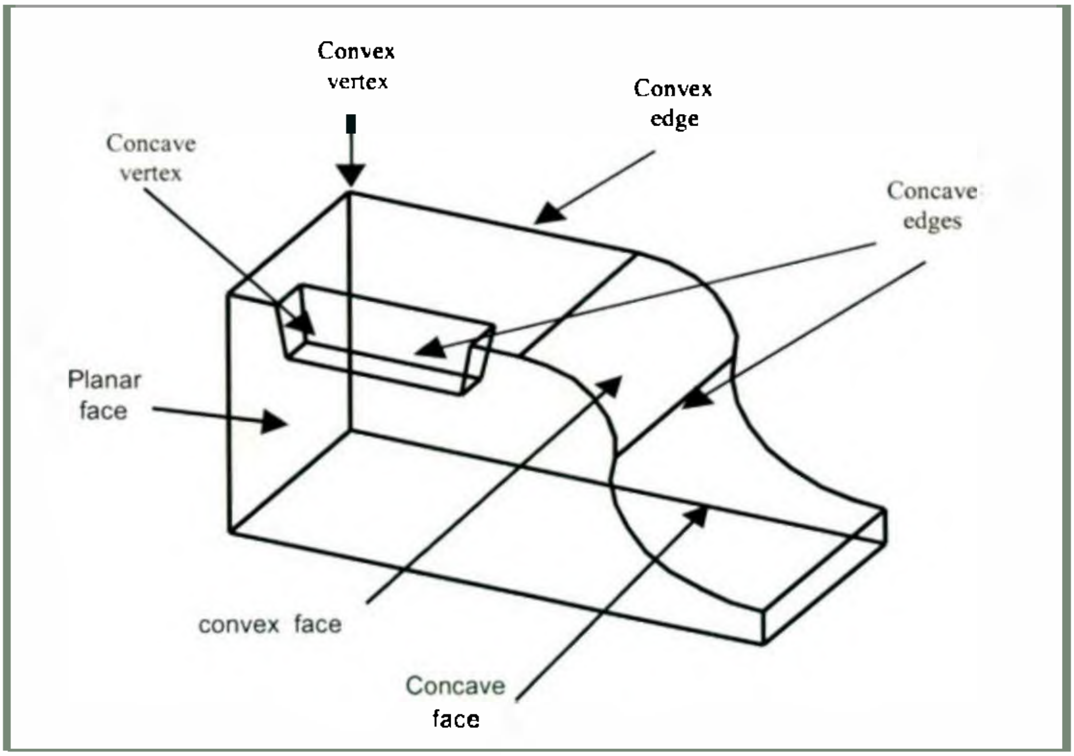


Figure 10. Classification of edges and vertices.

4.2.3 Concepts of face score and face vector

In resume a face consists of a surface plus a set of edges and vertices. Therefore, if a value is assigned to each one of these components based on their geometric and topological characteristics, then these values, which can be converted to a face, can be transformed into a score, namely Face Score (F_S). This F_S includes, implicitly, the face information and the information of the edges and vertices on the face.

The input for the neural network recognition system needs only a set of numbers, either integer or floating point. A B-rep solid model, however, contains complicated geometric and topological data for an object that cannot be simply evaluated by a set of numbers. Therefore, a technique to represent 3-D data as numbers is required, meaning that the pre-processor will attempt to convert 3-D objects to a set of n-dimensional face vectors. Because faces far away from the main face play a minor role in determining the feature, a nine-element vector is considered to contain enough information for this purpose. Nevertheless, if necessary, this number can be extended and a higher number of adjacent faces and/or faces with a higher adjacency relationship (farther away) can be considered in constructing the face vector.

All commercial B-rep solid modellers have a similar data structure. In order to describe completely an object, the information must consist of face equation (normal vector for a planar face and the axis direction for a cylindrical, torus or a conical face), the area of the face, and other necessary information such as the semi-vertical angle for a cone, etc. An edge is defined by the edge direction (direction along a straight line or the axis direction for a conic section), the concavity or convexity of the edge, and the necessary data to describe an edge such as the length of the edge. A vertex is defined by its geometric location. Finally, the relationship of the adjacent faces affects the formation of a feature, such as the connection (type of shared edge) between two adjacent faces.

The evaluation formula for the F_S can be written as:

$$Fs = f(F_g, E_g, V_g, A_t) \qquad [11]$$

Where:

Fs is the face score,

F_g is the face geometric information,

E_g is the edge geometric information,

V_g is the vertex geometric information, and

A_t is the adjacency among faces, edges and vertices.

F_S is a way to quantify geometrical characteristics of the faces in the object. Its value is based on three factors, Face-Geometric-Value (FGV), Edge-Score (E_S) and the Vertex-Value (VV). Five basic surfaces are used in this research to create each model, known as: plane, spline, sphere, cone and torus. FGV is assigned in basis to the convexity (2.0), concavity (-2.0), and plane or undefined (0.0) characteristic of each of these surfaces.

The E_S is also associated to the concavity (-0.5) or convexity (0.5) of the edges, which is defined by the combination of the faces sharing the edge. Table 8 presents the different combinations of faces and their resulting E_S.

Table 8. Face combination and corresponding E_S.

	Convex cone (CxC)	Concave cone (CcC)	Convex sphere (CxS)	Concave sphere (CcS)	Plane (P)	Spline (S)	Convex Torus (CxT)	Concave Torus (CcT)
Convex cone (CxC)	0.0	0.0	0.5	0.0	0.5	-0.5	0.5	-0.5
Concave cone (CcC)	0.0	0.0	0.0	-0.5	-0.5	0.5	0.5	-0.5
Convex sphere (CxS)	0.5	0.0	0.0	0.0	0.0	-0.5	0.5	0.0
Concave sphere (CcS)	0.0	-0.5	0.0	0.0	0.0	0.5	0.0	-0.5
Plane (P)	0.5	-0.5	0.0	0.0	0.5	**	0.5	-0.5
Spline (S)	-0.5	0.5	-0.5	0.5	**	0.0	-0.5	0.5
Convex Torus (CxT)	0.5	0.5	0.5	0.0	0.5	-0.5	0.0	0.0
Concave Torus (CcT)	-0.5	-0.5	0.0	-0.5	-0.5	0.5	0.0	0.0

** These options require a further evaluation, which is included in the program.

The VV is assigned as a function of the number and kind of edges converging into the vertex, according to the following equation:

$$VV = 0.5\,(Cx - Cc) \qquad [12]$$

Where;

VV is the vertex value,

Cx is the number of convex edges converging into the vertex, and

Cc is the number of concave edges converging into the vertex.

Finally, the F_S is computed based in the FGV and the VV of the face according to the following equation:

$$F_S = \frac{\sum_{i=1}^{NV} VVi}{NV} + FGV \qquad [13]$$

Where;

F_S is the face score,

VVi is the vertex value of the vertex i,

NV is the number of vertex in the face, and

FGV is the face geometric value of the current face being evaluated.

Finally, a Face Vector (FVector) is created for each face in the object. Each face in the object will become the evaluated face, in turn, whose F_S will be allocated to the fifth element of the FVector. Then the adjacent 'Sharing-Edge' faces are considered and their corresponding F_S will be allocated to the elements 4, 6, 3, and 7 from higher to lower score respectively.

In the event that there are less than four 'Sharing -Edge' faces, for a particular face, the remaining of these four elements will be set to zero. But, if there are more than four 'Sharing-Edge' faces, then only the four faces with the higher scores will be used in constructing the FVector. The reason for this is that the particular neural network architecture chosen in this research requires a fixed number of input values in the input layer.

The other four elements of the FVector will contain the F_S of the adjacent 'Sharing-Vertex' faces following the same pattern (2, 8, 1, and 9) and rules applied to the assignation of the adjacent 'Sharing-Edge' face scores. Figure 11 shows a typical FVector and its elements.

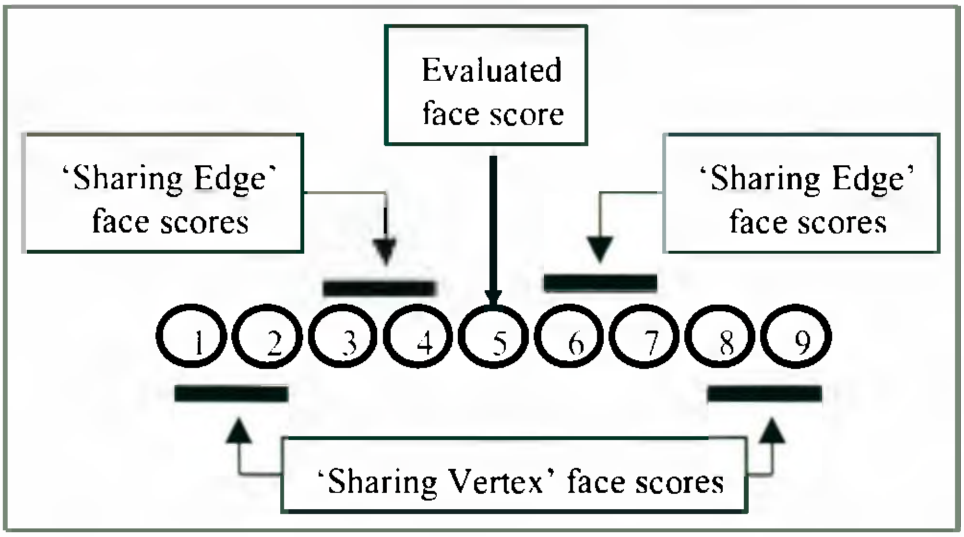


Figure 11. Typical FVector and its elements.

Since each face has its own FVector, which in some extension contains the information regarding the geometrical and topological characteristics of the evaluated face and its surrounding faces, then it is possible to say that faces with similar characteristics will have similar FVector. This is the fact used in this research to define different features, where each kind of feature maps to a particular pattern or FVector.

4.3 Feature Definition

According to the previous section, F_S depends on the face being evaluated and its boundary information. Lets use an example to describe the core of the feature definition approach used in this research. Considering a block evaluation we will see that all FVectors are the same for all its faces. This is due to the fact that the surrounding region of each face has the same information (all are planar faces with convex edges and convex vertices).

Since each face in the object has certain F_S, then a non-zero difference between a face score and its neighbouring faces' F_S indicates a topological or geometrical change between these faces, which form a region and the region may be defined as a feature. In other words, a region is considered as a feature based on a set of F_S changes between the face being evaluated and its surrounding faces. The definition of a feature face can be considered as the extension of the feature definition.

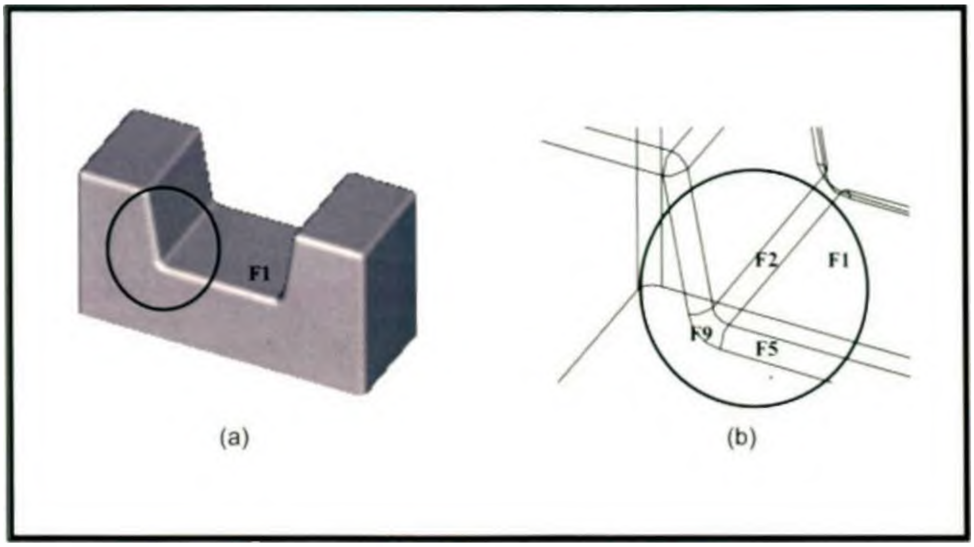


Figure 12. (a) Slot feature on a solid model. (b) Wire-frame detail.

A slot feature is used in Figure 12 as an example to show the face adjacency relationship in a solid model; face 1 (F_1 in figure 12.a) is used as the main face to define this particular feature. Figure 12.b shows a detail of the surrounding faces of F_1 in a corner so it is possible to observe that F_2 and F_5 have a sharing-edge relationship with F_1 but F_9 only shares a vertex with F_1. This fact will be used in the construction of the input vectors of the neural network.

Figure 13, shows the normalised face vector corresponding to the slot feature. Table 9 contains the face score calculations for each of the faces defining this feature. The last column of this table contains the normalised values of the face scores ranging between 0 and 1. Normalised values (N_v) are necessary due to the fact that neural networks can only handle data in the range of the activation function [0,1] (uni-polar) or [-1,1] (bi-polar), which simplify the input in the neural net.

The equation used to normalise the values to a uni-polar activation function, such as the one used in this application, is:

$$N_v = (F_S + 4) / 8 \qquad [14]$$

Where;

N_v is the normalised face score as to be used in the construction of the FVectors, and

F_S is the face score.

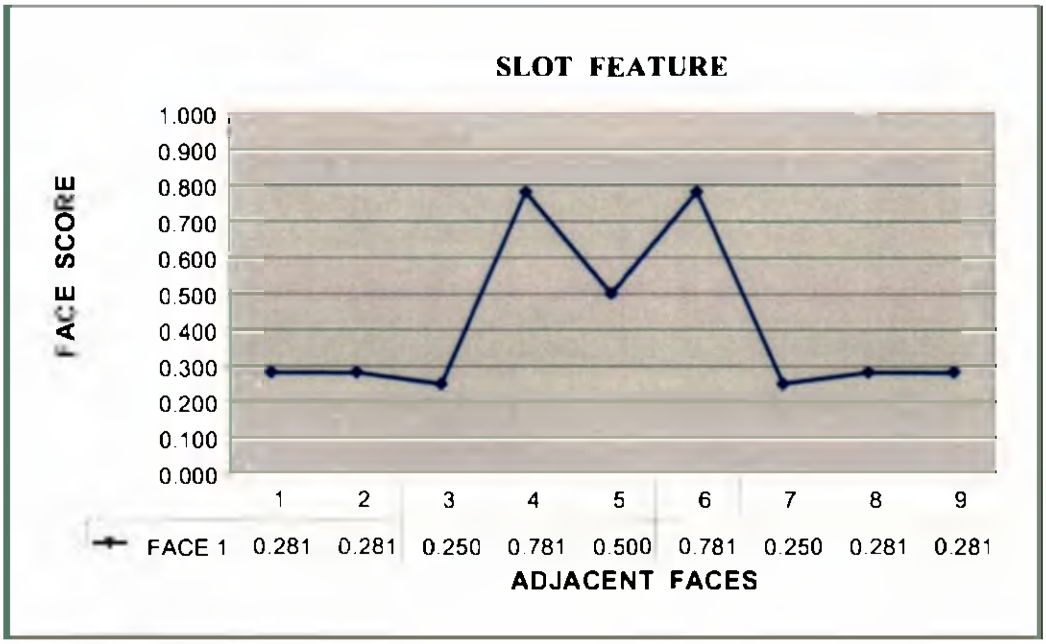


Figure 13. FVector corresponding to a slot feature.

F_S may have a maximum value of 4 for a face with just convex vertex, convex edges and convex surface and (-4) for faces with concave edges, concave vertex and concave surface.

Table 9. Face score calculations for the slot feature.

FACE No	VALUES	RESULT	NORMALISED (N_v)
1	(0.5 + 0.5 – 0.5 – 0.5)/4 + 0.0	0.0	**0.5**
2, 3	(0.5 + 0.5 – 0.5 – 0.5)/4 – 2.0	-2.0	0.25
4, 5	(0.5 + 0.5 + 0.0 + 0.0)/4 + 2.0	2.25	0.781
6, 7, 8, 9	(0.5 + 0.5 + 0.0 + 0.0)/4 – 2.0	-1.75	0.281

Typical FVectors for the eight features considered for recognition and evaluation in this research are shown in Figures 14 to 17.

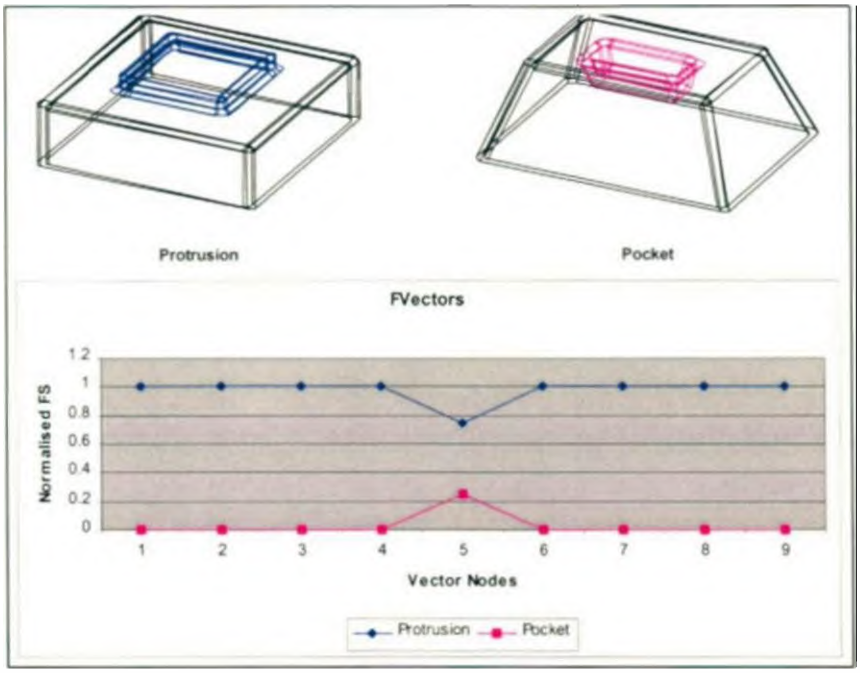


Figure 14. FVectors corresponding to Protrusion and Pocket features.

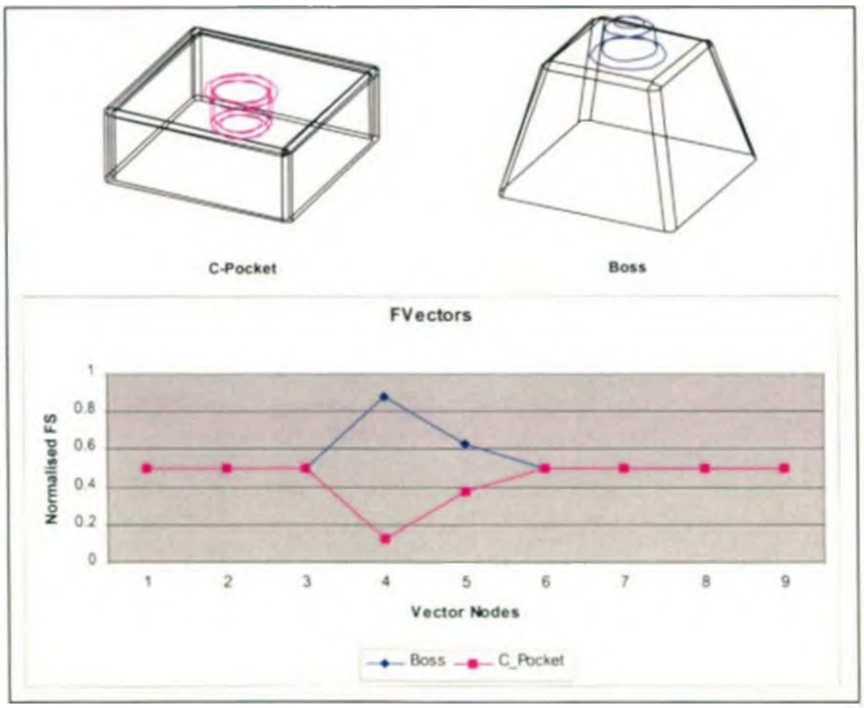


Figure 15. FVectors corresponding to Circular-Pocket and Boss features.

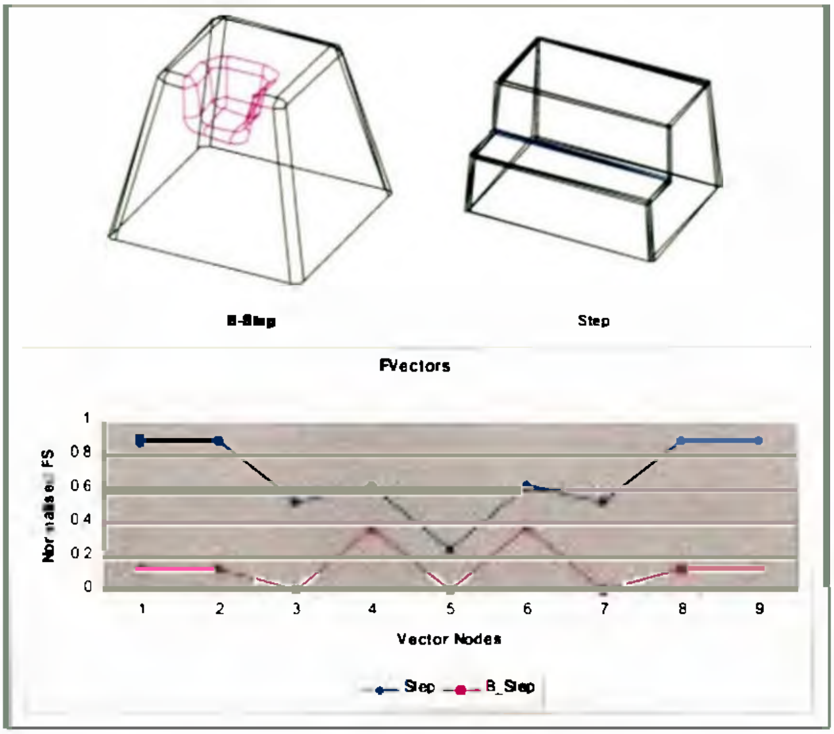


Figure 16. FVectors corresponding to Blind-Step and Step features.

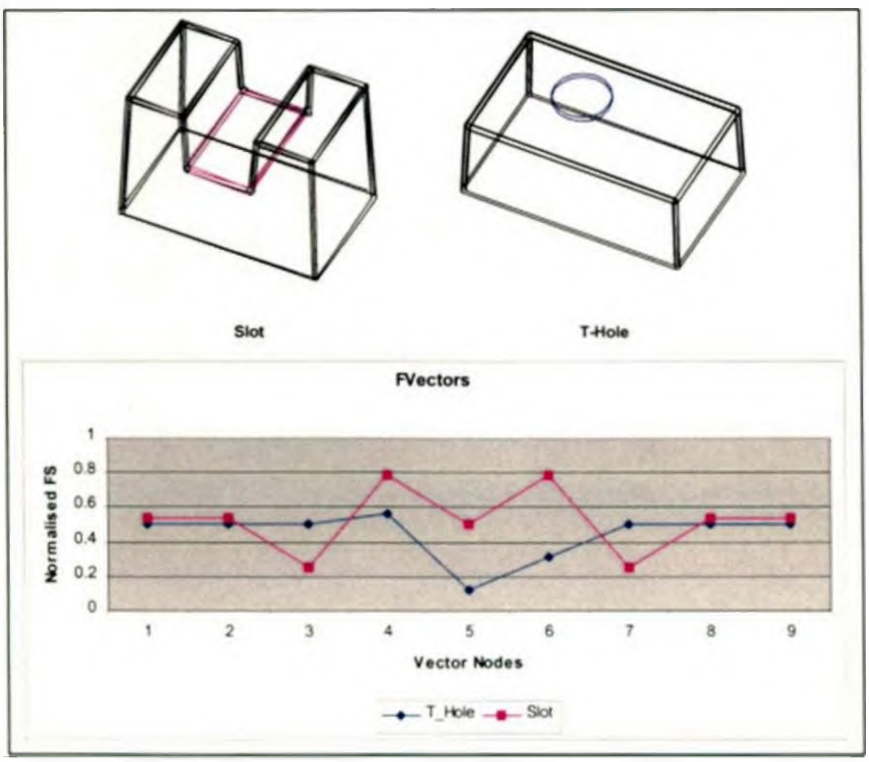


Figure 17. FVectors corresponding to Through-Hole and Slot features.

4.4 Training Set

A set of 36 synthetic sample parts was used to perform the training of the neural network system for feature recognition on reinforced plastic components. Each of these parts was designed as simply as possible to facilitate the training of the networks, but still being able to represent in full the characteristics of each feature making it possible to discriminate a face-feature from the other faces in the part.

Training parts are shown on Figures 18 to 23. All training parts were used for training of each neural network on the system. Parts were organised based on the particular feature to be recognised. Protrusion feature training parts are included in each one of the other series; therefore it does not have a separate series of parts to be used during training of its neural network.

As it was previously mentioned, the neural network system requires one network for each feature to be recognised. Therefore, independent training of each network has to be carried out, where all training parts are used but the learning input parameters are different for each network.

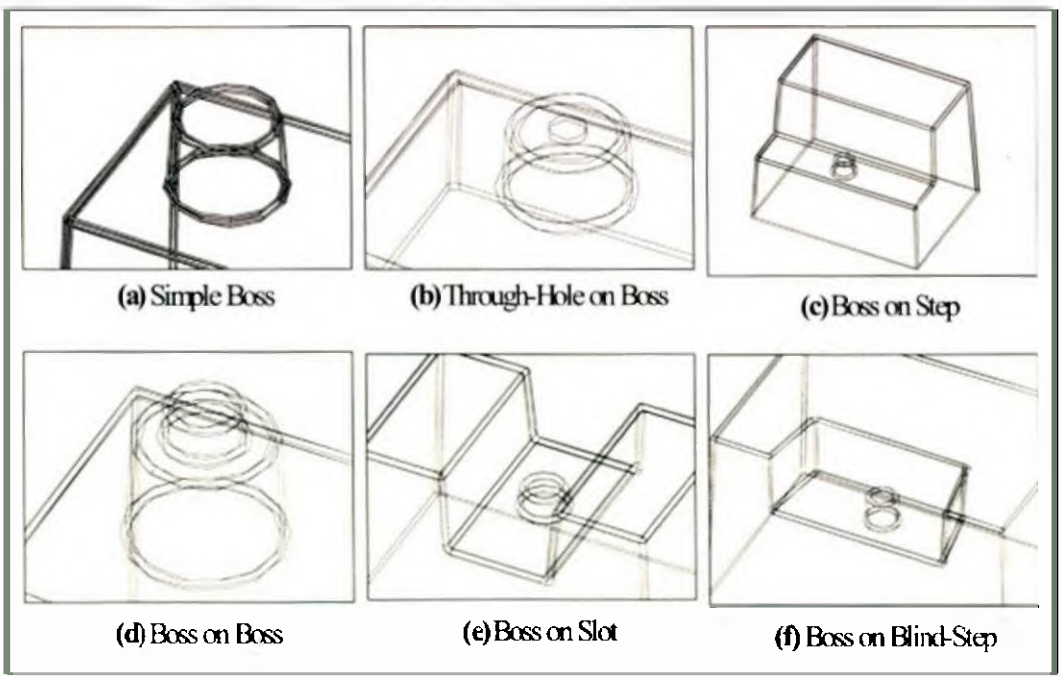


Figure 18. Boss training parts.

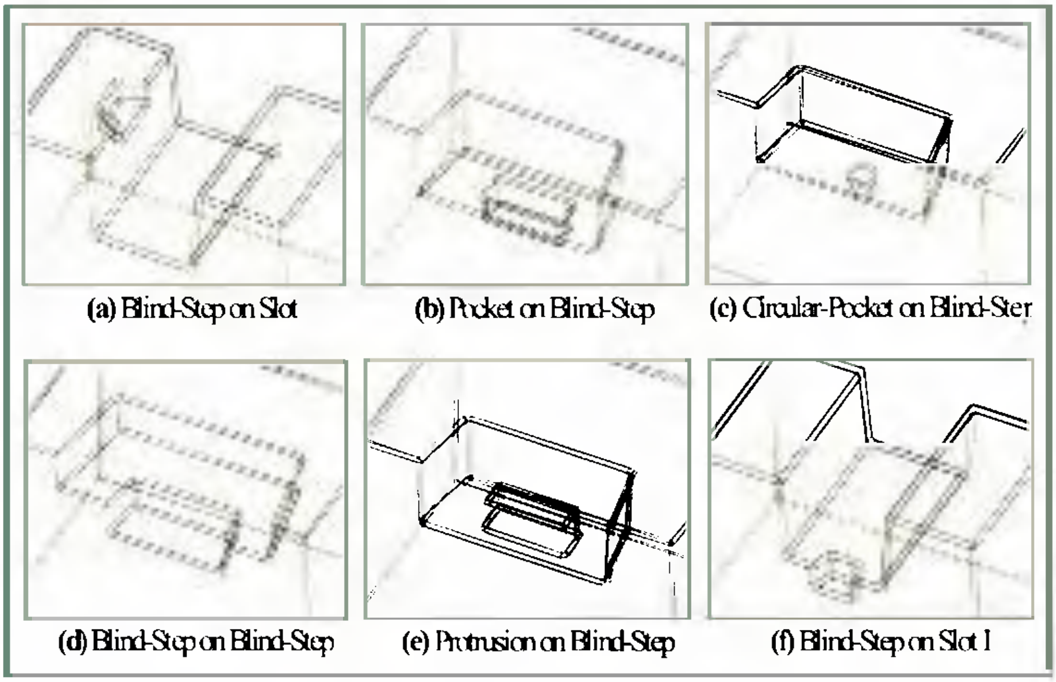


Figure 19. Blind-Step training parts.

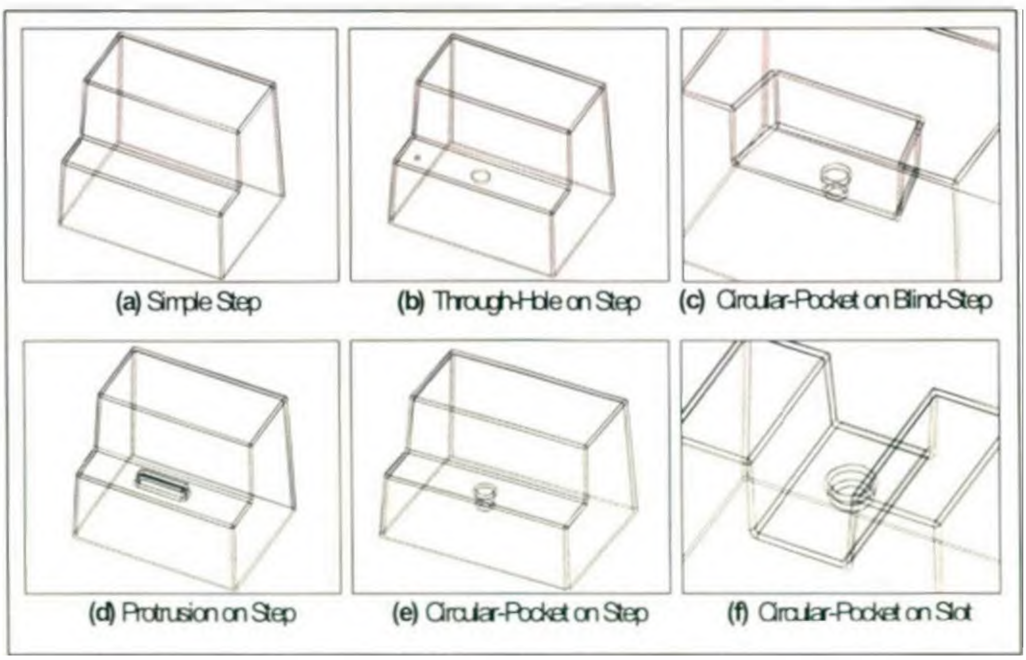


Figure 20. Step and Circular-Pocket training parts.

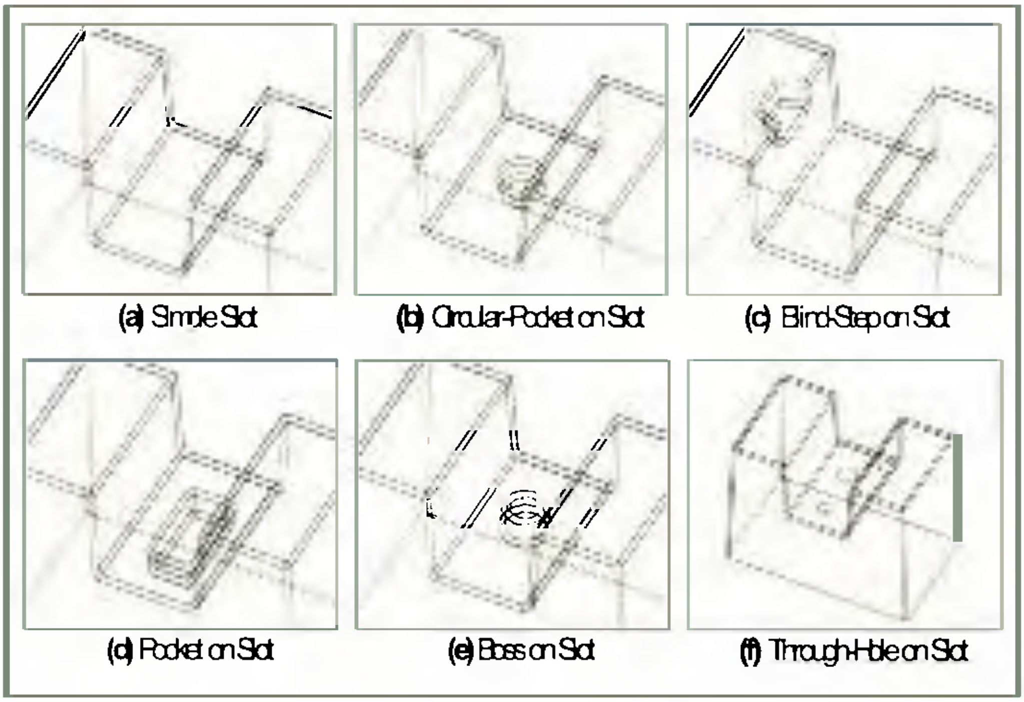


Figure 21. Slot training parts.

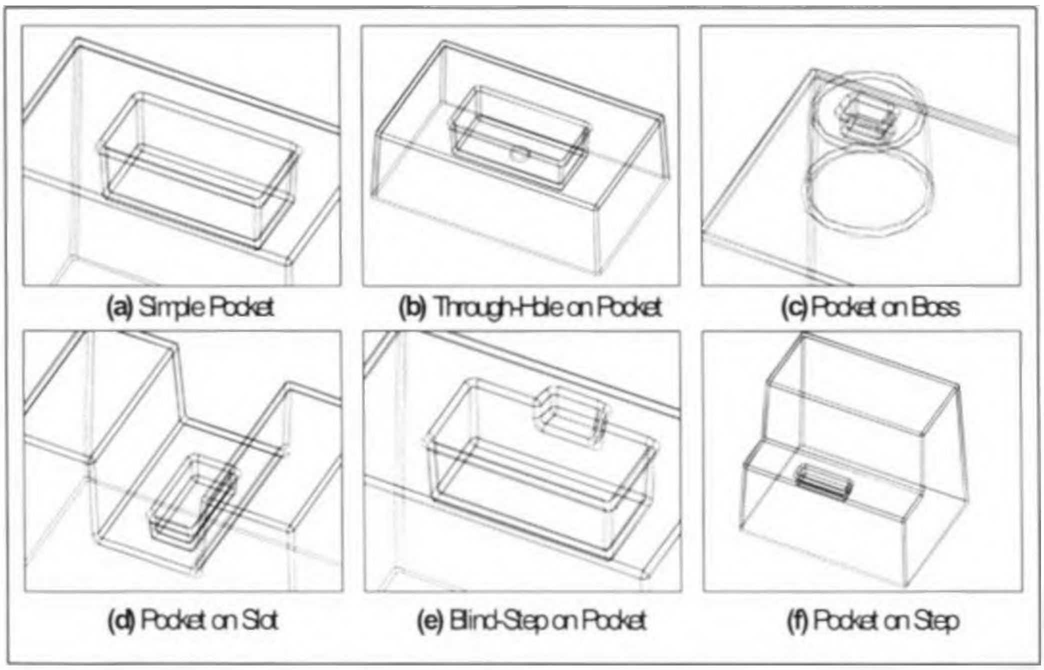


Figure 22. Pocket training parts.

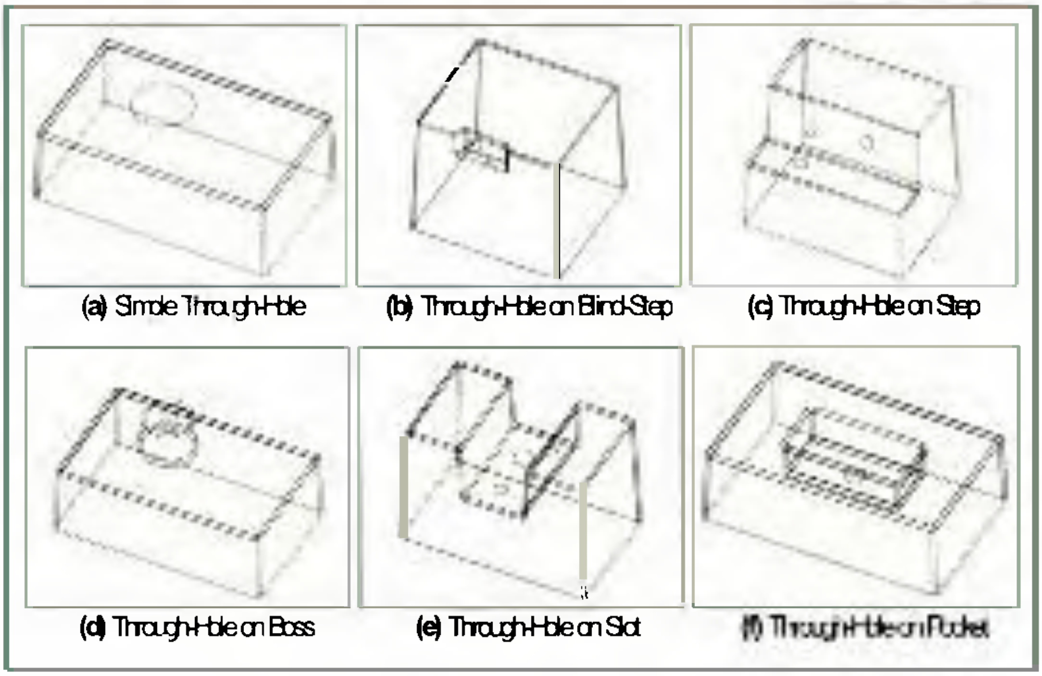


Figure 23. Through-Hole training parts.

4.5 The Neural Network System

SNNS (Stuttgart Neural Network Simulator) is a simulator for neural networks developed at the Institute for Parallel and Distributed High Performance Systems at the University of Stuttgart in Germany. SNNS was selected to carry out this research work based upon the net-creating and net-training features of the system, which allows a diversity of network configurations and several activation functions to be tried. The SNNS simulator consists of four main components: The simulator kernel, a graphical user interface, a batch simulator version, and the network compiler.

The simulator kernel operates on the internal network data structure of the neural nets and performs all operations on them. The graphical user interface XGUI, built on top of the kernel, gives a graphical representation of the neural networks and controls the kernel during the simulation run. In addition, the user interface can be used to directly create, manipulate and visualise neural nets in various ways. Nevertheless, XGUI is also well suited for inexperienced users, who want to learn about connectionist models with the help of the simulator. The on-line help system, partly context-sensitive, is integrated, which can offer assistance with problems during the user learning process or interpretation of results for more advanced users.

After an intense work of trial and error, where several network architectures were tested, it was found that a three-layer feed-forward network using a supervised learning algorithm was the most appropriate network to be used on this particular application. The final network architecture selected can be seen in Figure 24.

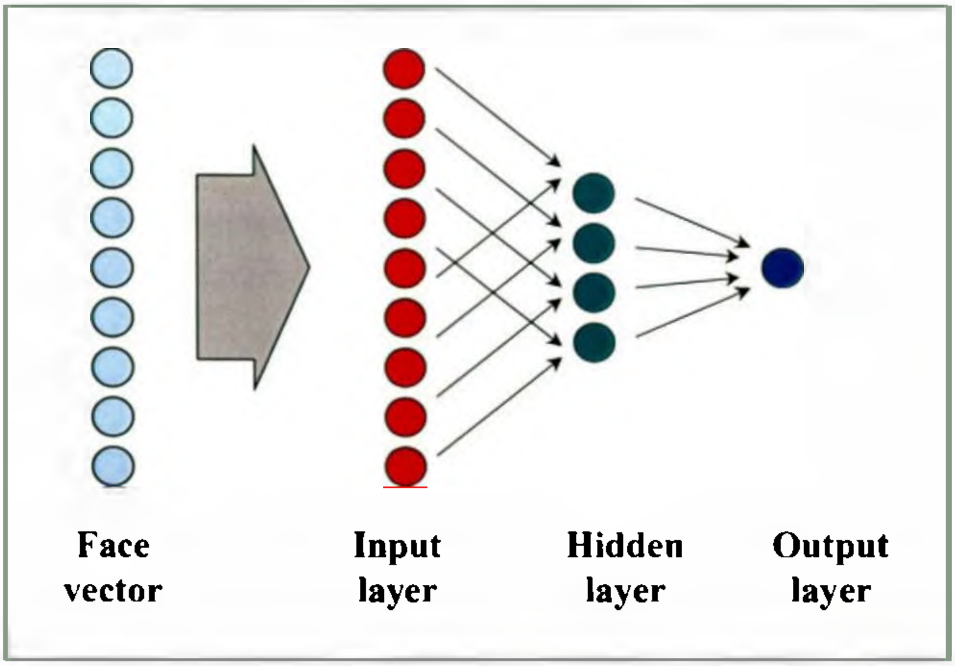


Figure 24. Neural Network Architecture.

Nine nodes or neurons corresponding to the nine elements of the FVectors form the first layer or input layer, which has a fixed number of nodes. Four nodes form the intermediate or hidden layer and finally, one node forms the output layer, which allows having enough number of combinations (2) of binary output (1 or 0) to represent the feature recognition. One neural network is required for each feature to be recognised.

Special attention was paid to the fact that the network should not be neither under-trained nor over-trained. Under-training a network means that it knows too little about the training set of data, therefore it will recognise or classify badly. On the other hand, if the network 'memorise' the training set, known as over-training, then it will not be useful for classification of a test set of data. Once the minimum test error is reached the learning process must stop, as shown in Figure 25.

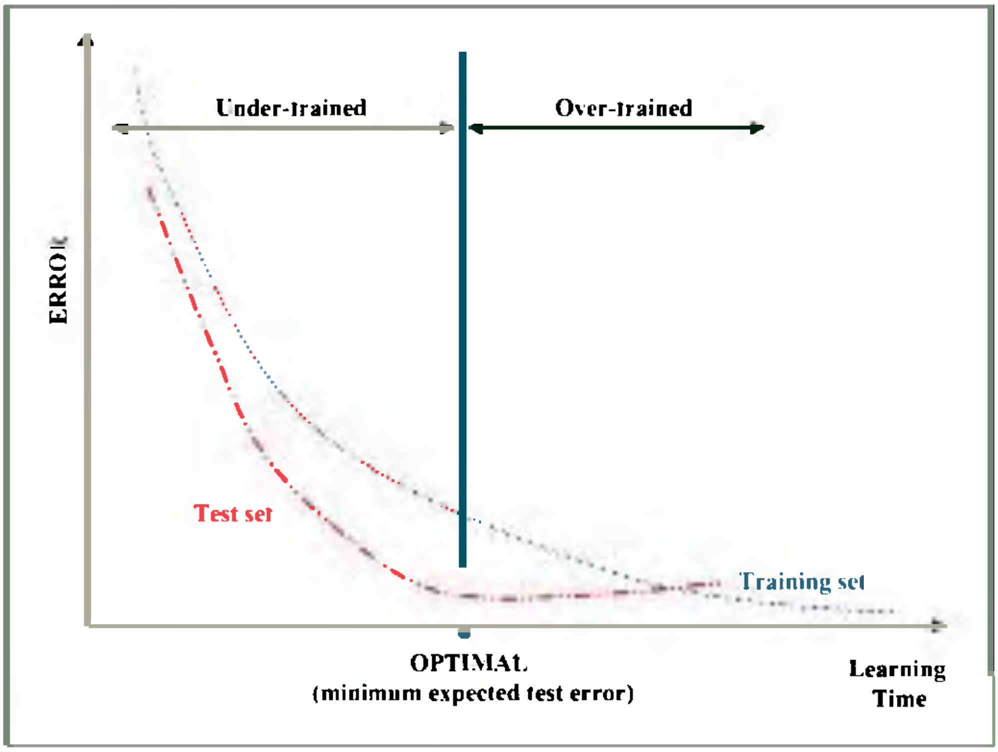


Figure 25. Criteria for stopping the training of a neural networks.

Training was made under supervised theory using a data set corresponding to all 36 sample-parts, which represent a total of 1520 faces with their corresponding FVectors. From this data approximately 15% was saved for validation. A minimum number of three thousand cycles of the complete data set was presented to each network in a random manner and after that training was stopped when a minimum test error was reached. The learning parameter α was fixed at a value of 0.2 for all networks and the learning function used was standard back-propagation.

The main properties of the neural network system chosen can be resumed as:

- The neuron is either active (i.e. ON) or inactive (i.e. OFF). It therefore has two discrete states and it can be considered essentially as a digital device.
- In order for the neurons to become active, a predetermined number of synapses must be excited within a specific period of time.
- The effect of connections between neurons may be excitatory or inhibitory (i.e. they are weighted)

- All neurons have a threshold. In order for a neuron to be activated, the sum of its weighted-inputs must exceed the threshold, although the threshold of individual neurons may vary.

- The structure of the connections does not change during training of the net.

Appendix 1 contains the network definition files corresponding to the eight neural networks created as part of the feature recognition system used in this research. A network definition file contains all information necessary to build the actual network, such as learning function, update function, number of units or neurons, number of connections, weight between connections and threshold or bias values of each neuron.

Once the neural networks were trained their corresponding variable values were integrated as part of the source code in the main program of FEBAMAPP as a Windows application, which was then used for feature recognition and manufacturability evaluation of such recognised features. The reason for integrating the NN parameters, with the main program, is that once the network is trained it will remain unchangeable. Therefore, all functions used for the network in the process of learning are no longer required and the global performance of the system can be improved in terms of execution time.

Appendix 2 shows a typical result of a test file including the input, output and expected value of each vector presented to the net for recognition. The sample result file of the neural network is called real1_slot4.res, which means that the neural network used is designed to recognise slot features and the test file presented to the network is the one that contains the FVectors of the object named real1. The highlighted FVector number #96.1 is showing an output value of 0.99675, which is larger than the threshold of recognition set to a value of 0.90, meaning that this particular face is recognised as a slot feature in the model. Since this research does not have particular interest in partial features, then those faces with significance factor lower than the threshold are not considered as recognised features or partial features.

Chapter 5

5 FEATURE EVALUATION

5.1 Introduction

Traditionally, functional teams or individuals perform tasks associated to the product development separately. Therefore, lack of communication between product development tasks often causes consistency problems in later manufacturing stages of the process. In recent years, the concepts of concurrent engineering have been proposed to overcome this problem. These concepts refer to the practice of co-ordinating various life-cycle values of products into the earlier stages of design. Thus, in addition to the creation of a product shape that meets functional requirements, the selection of a proper manufacturing process, assessment of manufacturability and assemblability are incorporated in the product design to achieve full functioning, higher quality and lower cost of products.

Manufacturability assessment, which plays an important role in integrated product and process development, involves evaluating the manufacturability of a design and modifying it into one that is functionally acceptable with the selected manufacturing process (Chen, et al, 1995). This research considers the use of features, as the key element, in the manufacturability evaluation of the proposed models bridging the existent gap between design and manufacture of reinforced plastics components.

Manufacturability assessment is a highly skill-intensive activity, and requires a wide variety of design expertise and knowledge of the manufacturing process. Because of these facts, a highly experienced designer always performs manufacturability assessment. However, a lot of trial and error still exists, and quality is not consistent. There is therefore a need to formalise and encode design knowledge to assist designers in creating manufacturable reinforced plastics parts with less design routines and try-outs.

Since the presence of a highly trained designer is not always possible, then encoding the knowledge in a series of production rules and the development of an expert system to perform manufacturability analysis seems to be an option to give SMMEs the technical support they need to improve their product development process.

Design-to-manufacture rules can be seen as critical relationships between design requirements and process capabilities (Syan and Swift, 1994). Process capability data is usually compiled and organised in such a way that constitutes the basis for the design rules, and these rules provide the boundary conditions that determine if a proposed design is feasible from its cost, quality and/or lead-time characteristics.

Engineers and designers in the plastics industry have compiled design rules from process capability data over the last few decades. But, explicit work in the plastic industry is usually considered commercially confidential, therefore it was necessary to perform a thorough analysis of mould and die design literature. Most of the information used to build the knowledge-based system and its explicit design and manufacturing rules were collected from the reinforced plastic enclosure industry, texts and handbooks related to this particular manufacturing process.

It is up to the manufacturing and the knowledge engineers to synthesise the rules from process capability data and industrial experience in such a way that can be used in developing a KBS for manufacturability analysis. Therefore, this research focused on getting the information necessary to develop the set of production rules necessaries for the manufacturability evaluation of reinforced plastics parts. This evaluation will be based on internal and external characteristics of the features being considered in this research.

5.2 Rule-Based Approach For Manufacturability Analysis

The evaluation approach proposed in this research considers firstly the internal characteristics of the feature in terms of dimensions, thickness, fillet radii and draft angle. Secondly, external characteristics that represent the position of the feature in relation to others feature in the model as well as in relation to the boundary edges of the part. Attention is focused on the manufacturing aspects, capabilities and limitations of the available reinforced plastics manufacturing processes.

The features considered for evaluation in this research are pocket, protrusion, circular-pocket, boss, through-hole, slot, step and blind-step. All of them are fully supported by the FEBAMAPP's feature recognition module developed as part of this research.

The following sections contain relevant information regarding design and manufacturing of reinforced plastics parts, in terms of their features' internal and external characteristics. This information constitutes the basis for the development of the feature-based manufacturability analysis system attempted as the main outcome of this research.

5.2.1 Pocket feature

Any hollowed feature in the surface of the part can be considered as a pocket feature, see Figure 26(a). The shape of this cavity can be square, rectangular, circular or irregular. The internal characteristics to be considered for evaluation of a pocket are its depth, bottom, top and between-walls fillet radii, and draft angle.

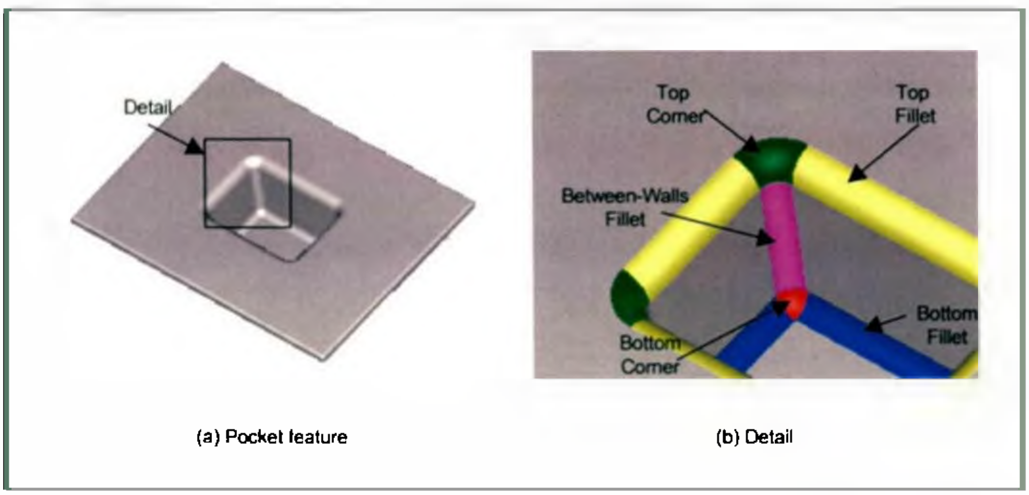


Figure 26. (a) Pocket feature. (b) Definition of fillets on a pocket feature.

The minimum depth of a pocket is driven by the manufacturing process to be used according to recommended fillet radii given on Table 3. Therefore, the minimum depth corresponds to twice the minimum fillet radii. According to Mr. Bryan Shepherd, Technical Director at one of our collaborating companies (Pearl GRP Industries LTD), it is a good practice that for the bottom, top and between-walls fillet of the pocket feature to keep the same radius through the feature. The reason behind this suggestion is that it will facilitate the manufacture of moulds and reduce the risk of trapped air between faces of the object during moulding processes. Figure 26(b) shows a detail of a corner on a pocket feature and describes the types of fillets and corners expected to be found on it.

In general, the concave-corners of a feature are made by blending three concave cone surfaces, which lead to different situations according to the characteristics of these cone surfaces. When the between-walls fillet radii is larger than the bottom fillet radii the blended surface created is a concave four-side spline surface, see Figure 27(a). Despite numerical controlled machines being able to follow spline surfaces, this kind of surface will unnecessarily increase the cost of the final mould.

When the between-walls fillet radii is smaller than the bottom fillet radii a concave three-side spline surface is generated at the corner, with even greater manufacturing inconveniences the previous case, Figure 27(b). Finally, when constant radii are then used in all three surfaces converging into the bottom corner, a concave sphere surface is created, which is more easy and economical to construct, Figure 27(c).

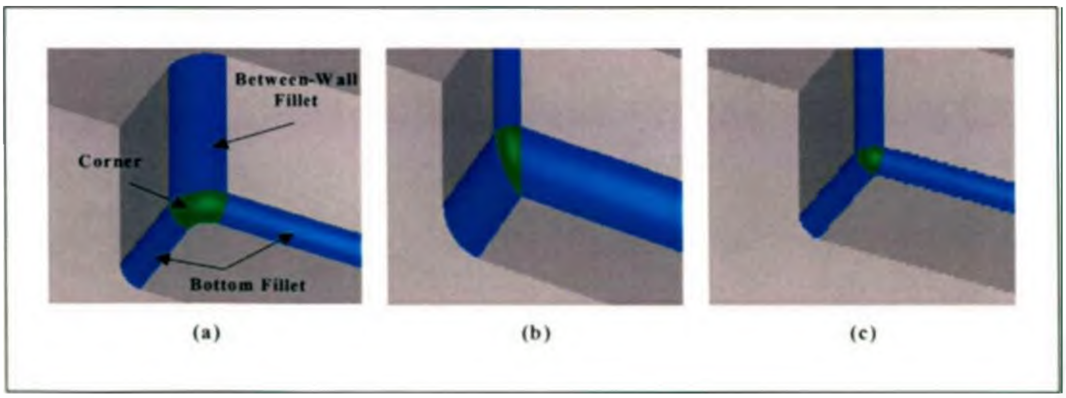


Figure 27. Concave surfaces generated by blending different fillets at the concave corner of a feature. (a) Four-side spline. (b) Three-side spline. (c) Concave sphere surface.

Regarding the top corners of a feature, it presents a different situation, where it is necessary to blend two convex and one concave cone-surface. In this case it does not matter what combination of radii are used, the blended surface in the corner will always be a four-side spline surface, as shown in Figure 28(a) and 28(b).

From the manufacturing point of view this situation is not a problem as long as the top edge fillet be kept constant all around the pocket feature. These rules and recommendations regarding bottom, top and between-walls fillets apply to all features with similar geometric configurations, as step, slot and blind-step.

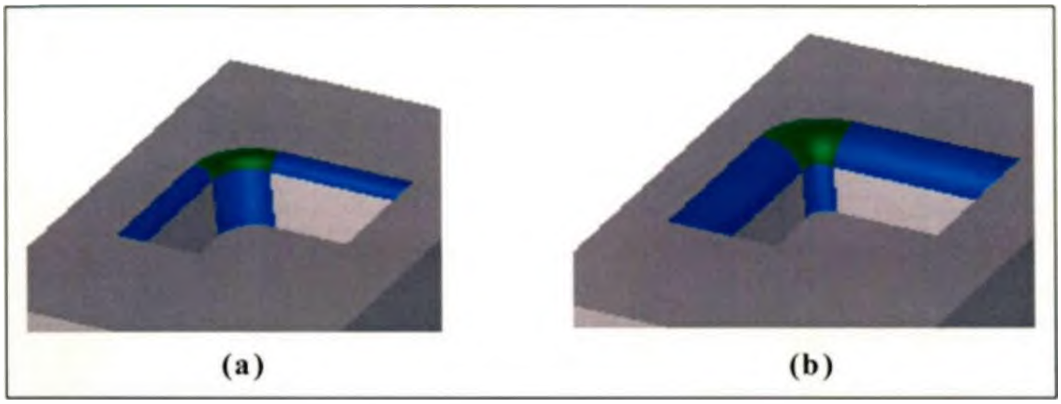


Figure 28. Surfaces generated by blending different fillets at the top corner of a feature: (a) and (b) both are four-side spline.

Recommended draft angle values are presented in Table 5, where it is possible to observe that they depend on the process selected and the depth of the walls. From the manufacturing point of view, it is necessary to check that draft angles are appropriated in each vertical wall of the feature. Therefore, each vertical wall must be evaluated calculating the angle between the normal vector of vertical walls and the pulling-out direction of the mould assumed to be the Z+-axis on the world co-ordinate system of the model.

Regarding external characteristics of pocket features, the most important to be considered are allowance to tool reach, closeness to adjacent features and to the boundary edges of the part, this is illustrated in Figure 29. It is necessary at this point to make reference to the fact that a different RPMP might have different requirements for external characteristics of features.

Tool-gap recommended for hand lay-up and spraying processes requires a minimum distance between the two vertical walls such that the laying-up and rolling tasks can be performed without interference. Recommendations regarding tool-gap are based upon typical tool sizes available in the market and to the minimum radii at the bottom fillets of the gap. The minimum distance recommended is 20 mm at the bottom of the gap between the pocket feature and any other adjacent feature or external boundary of the part.

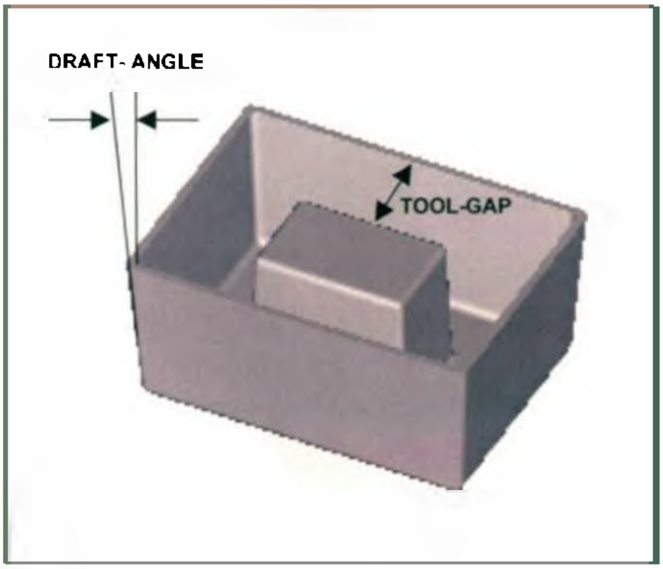


Figure 29. (a) Backside of a pocket feature.

For a pressure bag process the tool gap required is even larger, since the elastic bag is limited in its flexibility and it will not be able to reach the bottom of gaps smaller than 25 mm and depth larger than 35 mm. It would be possible to use deeper pockets as long as enough gap is provided between the vertical walls of the pocket and the adjacent features or external walls of the part.

For matched-die processes the tool-gap is limited mainly by the kind of reinforcement used and properties of the resin. There are some resins that flow easily but some others require vacuum and/or pressure assistance to be able to reach fine details in the mould.

5.2.2 Protrusion feature

Any outgrowth in the surface of the part can be considered as a protrusion feature, see Figure 30(a). The shape of a protrusion feature can also be circular (boss feature), square, rectangular or irregular. Again, internal characteristics to be evaluated in the protrusion feature are minimum gaps between vertical walls, radii of different fillets and draft angles, as shown in Figure 30(a, b).

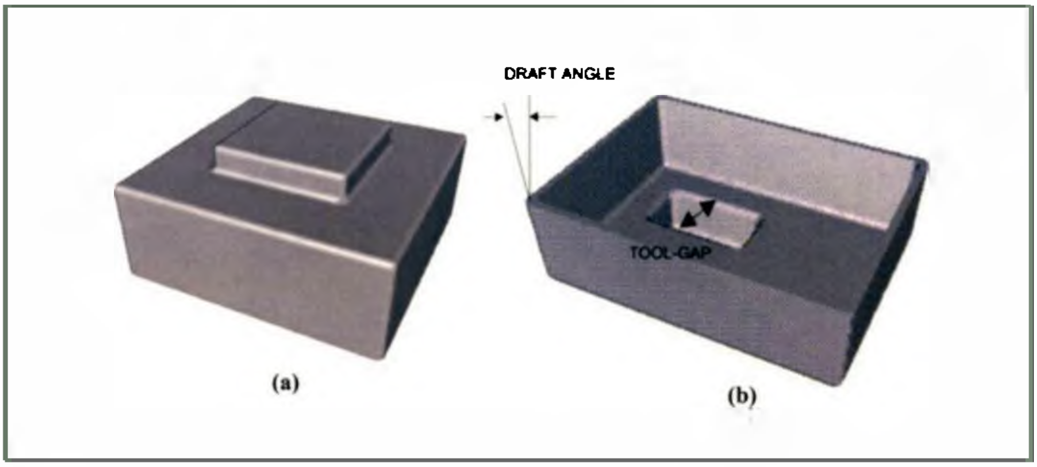


Figure 30. (a) Typical protrusion feature. (b) Rear-view showing internal characteristics of a protrusion feature.

For the protrusion feature also the minimum radii suggested in Table 3 drive the minimum height of this feature. The minimum gap between vertical walls will depend on the manufacturing process selected. In open moulding processes (hand lay-up or spray lay-up) there should be enough room for the rolling process after the resin and fibre are applied, therefore the minimum tool-gap value recommended is 45 mm. This value will be affected by the height of the protrusion where a ratio Tool-gap/Height > 1 is recommended for protrusions higher than 45 mm. For the pressure-bag process, an even larger tool-gap is required on this feature due to the difficulties of the bag to follow changes in the surface of the model. Consequently, the minimum tool-gap suggested is 60 mm and Tool-gap/Height ratios > 2, for protrusions higher than 60 mm are recommended. Figure 30(b) shows the rear-view of the protrusion feature. The same recommendations that apply to the draft angle in the pocket feature will also apply for the protrusion, recommended values being presented in Table 5.

If the location of the protrusion is not deep-nested (protrusion on top of protrusion) in a way that adjacent features interfere with the process then it should not present manufacturing difficulties. The distance between the base-fillet of the protrusion and the adjacent feature should be at least 25 mm to avoid trapped-air problems on open moulding process.

For the Pressure Bag process this distance should be large enough to allow the bag to follow the change in curvature in the surface of the part, therefore the minimum distance recommended between adjacent features is 20 mm. For matched die processes the minimum distance between adjacent features will depend on how thin the mould needs to be, and the rigidity required. For practical reasons it is recommended that this distance should not be less than 2 mm for this particular process.

With regards to the distance to the boundary edges of the part, this should not affect the stiffness of the product, and must not be smaller than 10 mm if the boundary edge of the part is flat. Otherwise, this distance has to follow recommendations according to the manufacturing process in use, with respect to the minimum radii and the blending of adjacent plane surfaces, see Table 3.

5.2.3 Circular pocket and boss features

Considering these features geometrically opposite to each other, it is possible to make a conjunct evaluation of their internal characteristics. For the circular pocket and open moulding processes, the minimum tool-gap distance is not a major problem since the material is layered from the rear of the part. Recommended values for open moulding processes are dependent on the depth of the pocket as shown in Figure 31.

For other processes recommendations given for the blind-hole featured in Figure 4 should be followed according to the process used. For protrusion features in open moulding processes, looking at the rear of the feature it seems as a pocket, therefore the minimum tool-gap recommended is 25 mm. The depth of the feature as shown in Figure 31, will dictate this value.

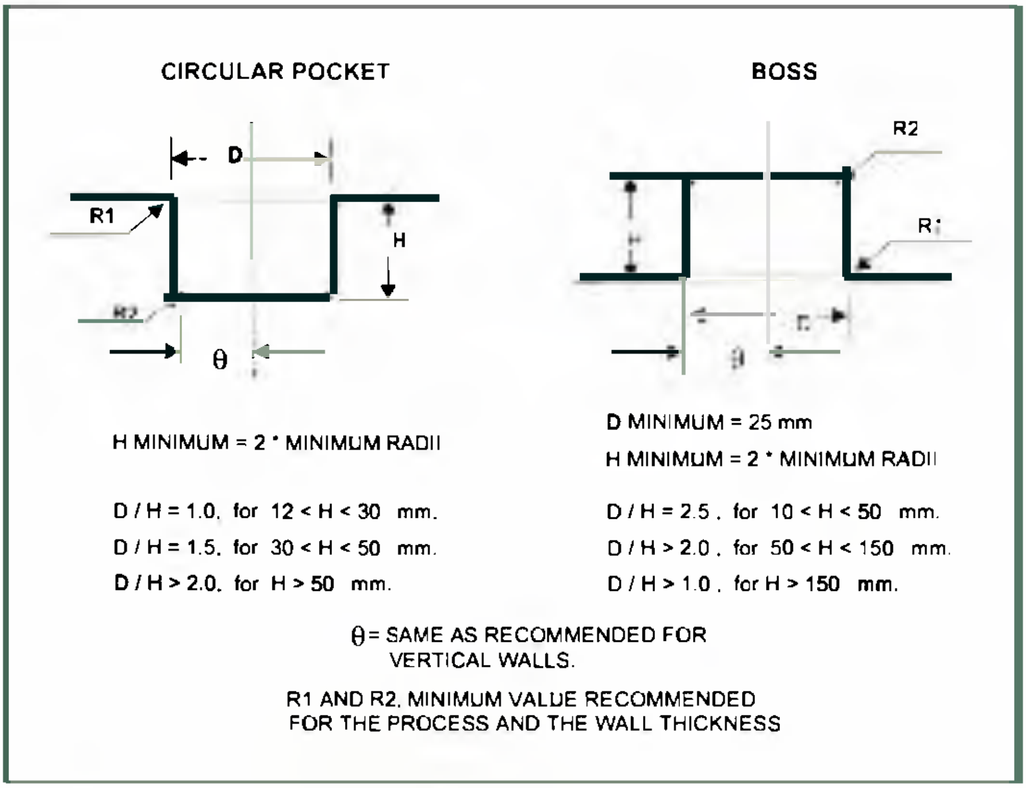


Figure 31. Recommended values for Circular Pocket and Boss features in open moulding processes.

Draft angles for both features will follow recommendations given in Table 5, and are process dependent and should not be less than 1 degree. For practical reasons the bottom and top fillets radii should follow recommended values given in Table 3 for the process used.

As for external characteristics, the distance to adjacent features is the most important for open moulding since it is necessary to provide enough space for rolling the air out of the resin, as shown in Figure 32. The minimum distance recommended between adjacent features is 25 mm, however it should be increased if the depth of the pocket is greater than 35 mm. As for other processes, the position of a feature in relation to adjacent features and/of boundary edges of the part is driven by the complexity of the part and the mould construction. This distance should not be so small that it compromises the strength of the mould or interferes with the free flow of the material during mould filling. Thus a minimum value between 5 to 25 mm is recommended, depending upon the material and process used.

Figure 32. Rolling task on a Pocket feature. Minimum tool-gap (T).

5.2.4 Circular and irregular through-hole features

As explained earlier, holes are one of the key features to be considered in designing a reinforced plastic product. Size and edge-finish of the hole defines the method that can be used to produce the hole in the final part.

Circular holes with a flat edge-finish with diameters up to 15 mm should be drilled after curing the product. For larger diameters, when the edge-finish required is flat, the drilling process is still recommended for simplicity and economical reasons, but sometimes mould-in process can be justified when saving material is important. The same approach can be used for flat edge-finish irregular holes where a pattern can be used to cut out the shape of the hole after curing.

Recommended draft angles for the bossing-edge are in Table 5. Minimum diameter (D) for bossing-edge circular holes depends upon the material used and recommended value is twice the thickness of the part. The length of the bossing-edge (H) should be at least equal to the thickness of the part. Details of these geometrical variables are presented in Figure 33.

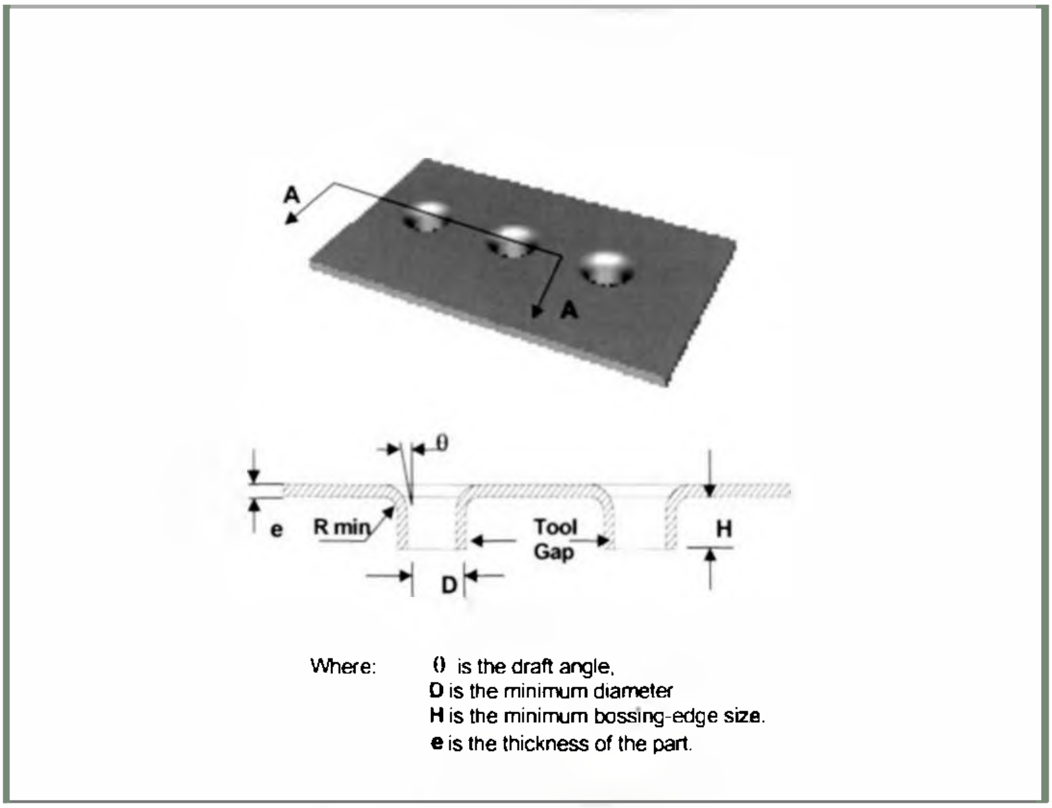


Figure 33. Bossing-edge holes and their geometric constraints.

In instances where the edge of the hole requires high strength, reinforcement in a boss-edge shape is recommended and the built-in-mould process is compulsory. The location between holes and distance to adjacent features must be considered in this case. A minimum recommended radii, as recommended in Table 3, must be used to set the minimum tool-gap distance as for any other feature.

For irregular holes, the rules for between-wall and upper fillet radii apply as in the case of pocket features. Special attention should be taken in relation to the length of the minimum bossing-edge size.

For external characteristics of these features the distance to adjacent features or tool-gap and the distance to the boundary edges of the part are important. In the open moulding processes sufficient room for rolling tools should be allowed, a minimum distance of 25 mm is recommended for built-in-mould flat-edge holes. For other processes the rules for pocket features apply. Minimum distance to the edges of the part of 10 mm is recommended for flat-edges holes. Despite the short length for boss-edges a draft angle is recommended, this depends on the process to be used.

5.2.5 Slot feature

The most important internal characteristic of the slot feature is the draft angle between the two opposite walls where the minimum angle recommended should follow the same rules as for the pocket feature in the selected manufacturing process, values are presented in Table 5. Also, the manufacturing process to be used, according to the recommended minimum fillet radii in Table 3, dictates the minimum depth of the channel and the minimum distance between the walls at the bottom of the slot.

External characteristics of the slot feature are also important. the distance to adjacent features is the main concern regarding the tool-gap required. The minimum tool-gap required will depend on the manufacturing process selected and values given for pocket features in section 5.1.1 should be followed.

5.2.6 Step and blind-step features

For these features the internal characteristic of fillets follow the same rules as for the pocket feature, where similar fillet radii are suggested for between-walls, and bottom and top fillets. In this way further complications in mould construction are avoided. As for the draft angle and top fillet radii, similar values to those suggested for pocket features are indicated for the step and blind-step features. Ultimately, neither nested steps nor nested blind-step features are recommended unless larger draft angles are given to facilitate the extraction of the moulded part.

5.3 Feature evaluation algorithm

After feature identification the next step, in the process of manufacturability evaluation, is transferring the internal and external characteristics of the feature into the manufacturability analysis module of the system. It is in this module of the system where the actual parameters of each feature are compared with the information stored in the database.

Topological and geometrical information of all faces belonging to the identified feature are used to verify particular production rules about materials and manufacturing processes in accordance with the information stored in the database of the system. Figure 34 presents a simplified algorithm of the evaluation process, as it is used by FEBAMAPP, to evaluate the features identified in the model.

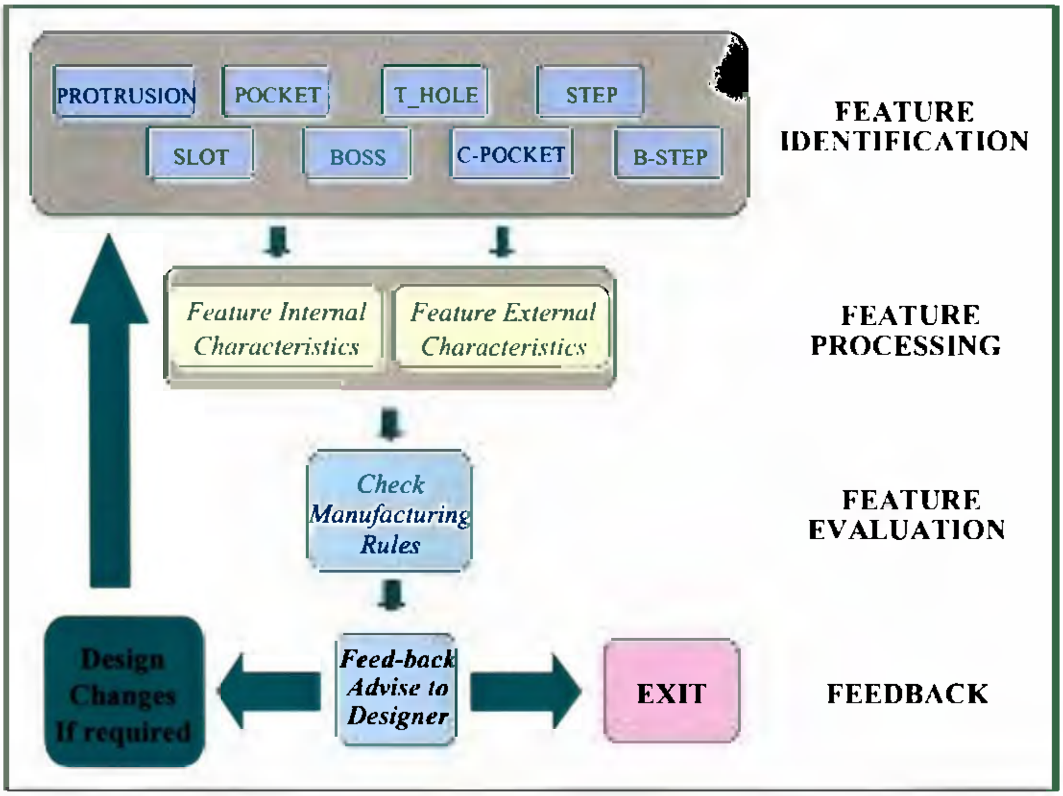


Figure 34. Algorithm used for feature-based manufacturability analysis.

Since each feature type has its own internal and external characteristics then each of them require a separate series of rules that need to be verified during the evaluation process. Furthermore, because the capabilities and limitations of each material and process available to the manufacturing of reinforced plastics components are different from each other, then along with the actual dimensions of the feature the information regarding intended materials and manufacturing process is required for the evaluation of the features.

The sequence of events during the analysis process is as follows:

- Internal and external characteristics of the feature being evaluated are passed from the post-processing of SAT file module to the manufacturability analysis module.

- Information in agreement with the capabilities and limitations of the selected combination of materials and manufacturing process, in terms of target fillet radii, draft angles, tool-gaps, etc., is retrieved from the system database and passed to the manufacturability analysis module.

- The corresponding set of production rules is applied to verify the status of all the parameters and variables related to the manufacturability of the feature.

- In the event of manufacturing-related problems being identified, during the application of the set of production rules, then some suggestions are given to the designer to improve the quality of the design in terms of its manufacturability. These suggestions are not for the complete model of the part but for those portions of the model that include the feature or features which may represent problems at manufacturing stage.

- Finally, if the designer makes some changes in the original model, the full process of manufacturability can be applied to the new model. Because any change in the solid model has to be done in the solid modeller then it is not straight forward the application of the manufacturability module to the new changes in the model, and the process must start from the beginning with the creation of the new SAT file of the model.

5.4 Sample of a Feature Evaluation

As an example of the application of the production rules for the manufacturability evaluation, lets consider the boss feature presented in Figure 35. The top face F1 is used to identify the presence of the feature, subsequently it is necessary to evaluate the whole geometry of the feature and its associated faces F2, F3, F4 and F5. Faces F2 and F4 are made out of a torus-surface and F3 from a cone-surface.

Figure 36 shows defining geometrical parameters of a typical torus-surface. As for the cone-surface it is defined by an elliptical single cone, which consists of a base ellipse and the sine and cosine of the major half-angle of the core of the cone. The polarity (sign) of the trigonometric functions defines the slant of the surface of the cone and the sense of the surface. Figure 37 shows the geometrical definition of a cone-surface.

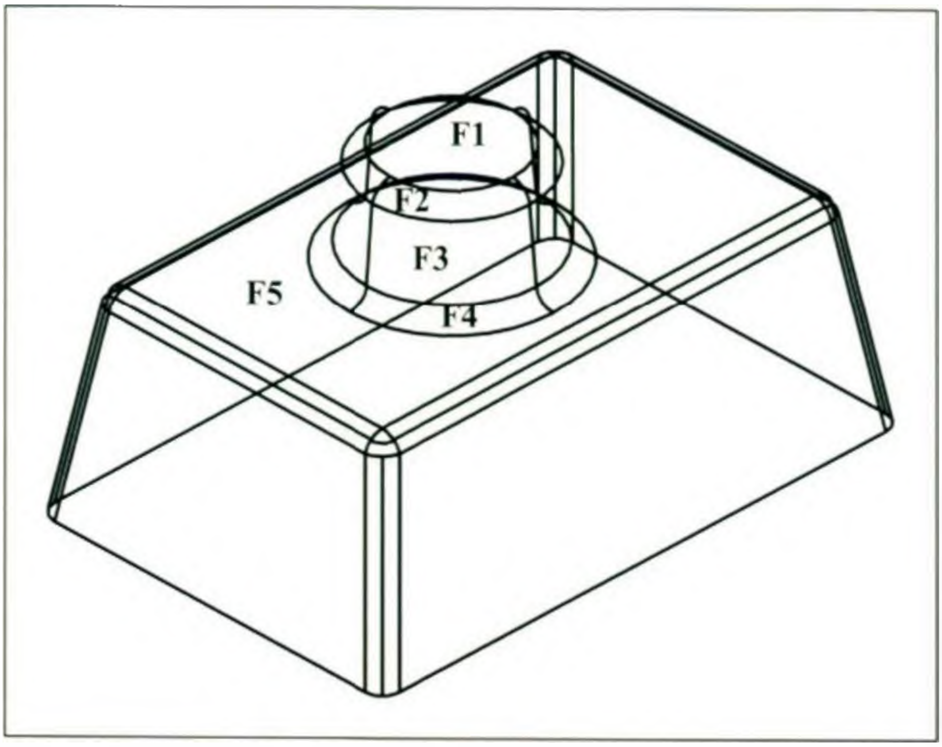


Figure 35. Faces in a Boss feature.

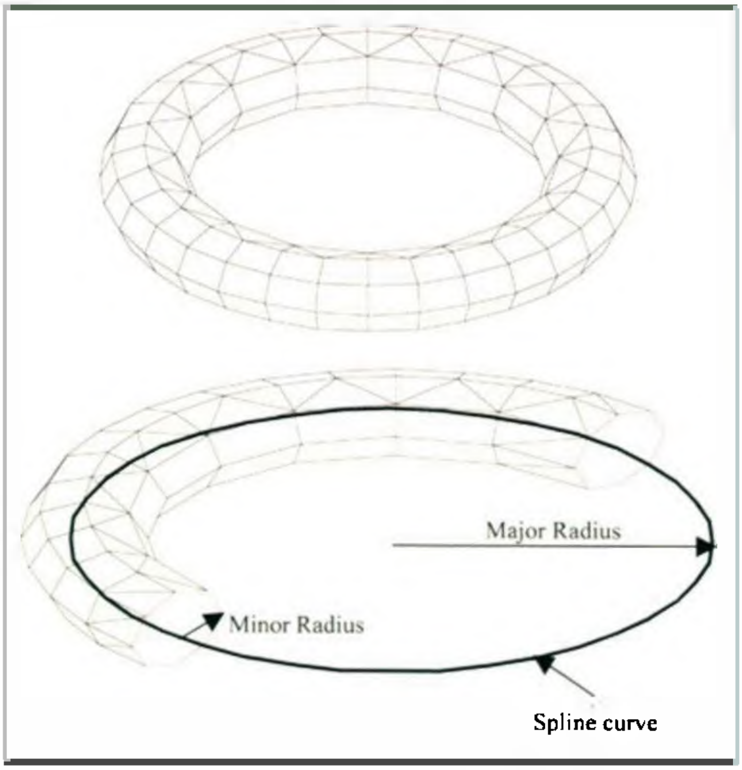


Figure 36. Defining geometrical parameters of a Torus-Surface.

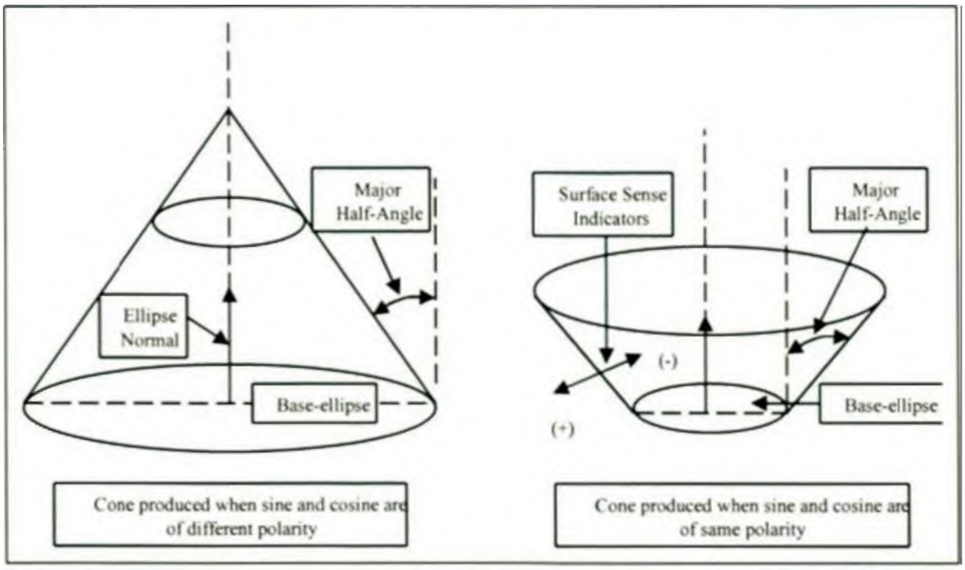


Figure 37. Defining geometrical parameters of a Cone-surface

Information regarding internal characteristics of the boss feature is obtained from the database of the CAD-model following the description and defining parameters of each surface type. On the other hand, information regarding external characteristics of the boss feature can be derived from the entities stored in the database of the part. For example, the minimum distance between the surface of the boundary of the convex torus at the base of the boss feature (face F4 in Figure 35) and the edges of the planar surface corresponding to face F5, are calculated using trigonometric relationships between a circle and straight lines. All references to dimensions used for the evaluation of this Boss feature are made to the faces indicated in Figure 35.

The sequence of events for the evaluation of the Boss feature, and in general for all features, is as follows:

1. **Materials and processes selection:** The combination of resin and reinforcement materials will drive the options available for the manufacturing processes. In the current example a materials combination of thermosetting polyester resin and E-Glass reinforcement is selected. Therefore, it leaves Hand Lay-up, Spray Lay-up and Vacuum Bag as the options available for the manufacturing process to be used in the analysis. Spray Lay-up is selected for this sample and as previously stated the target values for the parameters to be evaluated in each feature depend on the

combination of materials and manufacturing process selected for the simulation.

2. **Target values of the feature parameters:** The set of target values for the feature parameters are then searched in the database of FEBAMAPP and they are as follows:

    - Tool-gap at the top of the Boss feature = 25 mm, this dimension corresponds to the diameter of the circular surface of face F1.

    - Top fillet radius = 6.4 mm, this value is recommended according to the values given in Table 3 for the selected manufacturing process. This dimension corresponds to the face F2.

    - Regarding the draft angle there is a recommended value ranging between 0.5 and 10 degrees, depending on the depth of the vertical wall of the Boss feature according to the values given in Table 4 and Table 5. Since the depth of this Boss feature is 45 mm, then:

      Draft angle = 3 degrees.

      This dimension corresponds to the slant of the face F3.

    - Bottom fillet radius = 6.4 mm, this value is recommended according to the values given in Table 3 for the selected manufacturing process. This dimension corresponds to the face F4.

    - Tool-gap at the bottom of the Boss feature = 15 mm. This variable considers the distance between the bottom fillet of the Boss feature and the closest feature or external edges of the part.

3. **Application of the set of production rules:** The rules are applied in a sequential order as follow:

    - **IF** diameter of face F1 ***is less than*** **TARGET TOOL-GAP** at the top of the Boss feature, **THEN** the tool-gap at the top of the Boss feature is too small. **ELSE** the tool-gap at the top of the Boss feature is OK.

- **IF** minor radius of torus face F2 ***is less than*** **TARGET TOP FILLET RADIUS**, **THEN** the **TOP FILLET RADIUS** is too small. **ELSE** the **TOP FILLET RADIUS** is OK.

- **IF** slant of the cylinder face F3 ***is less than*** the **TARGET DRAFT ANGLE**, **THEN** the **DRAFT ANGLE** is too small. **ELSE** the **DRAFT ANGLE** is OK.

- **IF** minor radius of torus face F4 ***is less than*** the **TARGET BOTTOM FILLET RADIUS**, **THEN** the **BOTTOM FILLET RADIUS** is too small. **ELSE** the **BOTTOM FILLET RADIUS** is OK.

- **IF** the closest distance between the torus face F4 and the edges of the face F5 ***is less than*** the **TARGET TOOL-GAP** at the bottom of the Boss feature, **THEN** the **TOOL-GAP** at the bottom of the Boss feature is too small. **ELSE** the **TOOL-GAP** at the bottom of the Boss feature is OK.

4. **Results of the evaluation**: Comparing the actual internal and external characteristics of the feature with the target values retrieved from the database, which should match the materials and manufacturing process combination make the manufacturability analysis of this feature. The results from such evaluation are:

   - Actual diameter of face F1 is equal to 5.0 mm, which ***is less than*** the **TARGET TOOL-GAP** of 6.4 mm **THEN** the **TOOL-GAP** at the top of the Boss feature is **TOO SMALL**.

   - Actual dimension of the minor radius of torus face F2 is equal to 5.0 mm, which ***is less than*** **TARGET TOP FILLET RADIUS** of 6.4 mm **THEN** the **TOP FILLET RADIUS** is **TOO SMALL.**

   - Actual slant of the cylinder face F3 is equal to 2.5 degrees, which ***is less than*** the **TARGET DRAFT ANGLE** of 3.0 degrees **THEN** the **DRAFT ANGLE** is TOO SMALL.

- Actual minor radius of torus face F4 is equal to 5.0 mm, which ***is less than*** the **TARGET BOTTOM FILLET RADIUS** of 6.4 mm **THEN** the **BOTTOM FILLET RADIUS** is **TOO SMALL**.

- The actual closest distance between the torus face F4 and the edges of the face F5 is equal to 5.0 mm, which ***is less than*** the **TARGET TOOL-GAP** of 15.0 mm at the bottom of the Boss feature, **THEN** the **TOOL-GAP** at the bottom of the Boss feature is **TOO SMALL**.

5. **Report of results**: FEBAMAPP uses a series of dialog boxes for displaying the results from the manufacturability evaluation. A typical result dialog box uses the identification tag number of the faces being evaluated and the status of the variables being considered for the evaluation in each feature. A sample of this series of dialog boxes is included later in chapter 6 when a sample run of FEBAMAPP is presented as part of the results chapter.

Chapter 6

6 SYSTEM IMPLEMENTATION

6.1 Introduction

Developing an expert or knowledge-based system is never a straightforward work, and developing FEBAMAPP wasn't either. To arrive at the final architecture of the system, and to decide about the appropriate tools to be used for developing each module of the system, several issues were studied and it is the intention in this chapter to point out some of those that were explored along the research work.

According to the natural flow of information in the system the consideration about developing tools to be chosen were as follows:

- By-directional data exchange between the solid modeller used by the designer and the FEBAMAPP system.
- Design and training of the appropriate NN architecture to solve the feature recognition problem stated as target of the application.
- Development of the inference engine to perform the feature evaluation or manufacturability analysis of the model. This work is based on a set of production rules related to the design and manufacture of reinforced plastics parts developed as part of this research.
- Report and visual feedback of the manufacturability analysis results.

6.2 By-Directional Data Exchange

In our attempt to develop an application able to work using models developed in different solid modellers and platforms, a first approach was to use an international data exchange standard. Therefore, an analysis was carried out of the advantages and disadvantages of the Initial Graphics Exchange Specification (IGES), the Exchange of Product Data (STEP), the Data Exchange File (DXF), and the ACIS Text File (SAT) standards.

The IGES standard was developed in the later 1970s and adopted by the ANSI in 1981. This standard was developed mainly by major US CAD vendors, and employed as the format for the transfer of an ASCII file capable of being exchanged between any two systems. The first version of IGES used geometric entities as a basic building block and allowed 34 different types of entities to be used.

In the 1989 version 4.0 was introduced and for the first time IGES incorporated some facilities for the exchange of data describing constructive solid geometry (CSG) models. The alternative boundary representation (B-Rep) of solids was incorporated in IGES 5.0 at the early 1990s.

The IGES standard is essentially a specification for the structure and syntax of a neutral file in ASCII. The ASCII file is divided into 80 character records (lines), terminated by semi-colons and subdivided into fields by commas. The five sections of the file are:

- **The start section**, which is set up manually by the user initiating the IGES file, and which contains information that may assist the user at the destination, such as the features and specs of the originating system.

- **The global section,** which provides in 24 fields the parameters necessary to translate the file, including version of the IGES processor, precision of integer, floating-point and double precision numbers, drafting standards, etc.

- **The directory section,** which is generated by the IGES pre-processor, and which contains an entry for each entity in the file comprising a code representing the entity type and sub-type and pointers to the entity data in the next section.

- **The parameter data section,** which contains the entity-specific data such as co-ordinate values, annotation text, number of spline data points and so on. The first parameter in each entry identifies the entity type from which the meanings of the remaining parameters may be derived. Each entry has a pointer to the directory entry for the entity.

- **The termination-section**, which marks the end of the data file, and contains subtotals of record for data transmission check purposes.

Because of the particular format chosen for ASCII files, they are rather long, and substantially bigger than the CAD system data files that they represent. Also, and perhaps because the vagueness in the specification of the file they tend to be unreliable (McMahon and Browne, 1993).

Although IGES is the dominant standard for CAD data exchange, a number of alternatives or variant standards have been developed over the years, and furthermore there has been some dissatisfaction in the underlying basis for IGES. These factors have led to efforts to develop an agreed international standard to integrate the previous work, and to provide an improved fundamental basis for standard activities in this area. Various projects and associated work in the area have been drawn together by the ISO into a single unified standard called the Standard for Exchange of Product Data (STEP).

The STEP standard improves upon IGES by incorporating a formal model for the data exchange, which is described using a data modelling language called Express that was developed specifically for STEP. In IGES the specification describes the format of a physical file that stores all of the geometric and other data. In STEP the data is described in the Express language, which then maps to the physical file. The physical file does not then need to have a definition of how, for example, a point should be represented, but rather how Express models are represented in the file.

The Express language uses the entity as its basic element, which is a named collection of data and constraints and/or operations on that data. The entity data is expressed as a collection of attributes, which may be of a variety of types including strings, real and integer numbers and logical or Boolean values, and ordered or unordered collection of these termed arrays, lists, sets and bags. The attributes may also be references to other entities, or again to arrays, lists or sets of these. A collection of definitions of entities, and of the data types and constraints associated with these, is known as a schema

At the present time, work is still continuing on the development of STEP. The physical file specification has been completed and approved as an ISO standard. Significant progress has also been made in the specification of Express, and in the storage of geometry within STEP, but the application models and protocols are still under development (Shaharoun, et al, 1998).

In recent years CAD systems based on personal computers (PCs) have come to dominate the CAD market in terms of number of users. Of the software written for PCs, one program, AutoCAD by Autodesk Inc., has had a large market share and has been very influential. This is particularly true in the SMMEs dedicated to the manufacture of reinforced plastics parts in our target market for the use of FEBAMAPP.

The way AutoCAD has in part captivated a large share of the market is by the approach the company has adopted for making it relatively straightforward for third-party software vendors to develop software to work with AutoCAD or with AutoCAD files. One way in which this is done is by having different formats for the storage of files. Some of them are in a compact binary form and others in a readable form using ASCII. The format of this later form is used in files of the type DXF (short for Data Exchange File).

The DXF format is quite verbose, and uses one line for each data item. For example the definition of a single line in the plane XY might be as follows (comments in brackets):

LINE
8
0
10
-2.154 (first x co-ordinate)
20

1.315 (first y co-ordinate)

11

8.341 (second x co-ordinate)

21

10.5 (second y co-ordinate)

0

More recently, AutoCAD included ACIS modelling, which is an object-oriented three-dimensional (3D) geometric modelling engine designed to be used as geometric foundation within virtually any end user 3D modelling application.

ACIS models can be saved as binary (*.sab) or text files (*.sat), also known as SAT files. This kind of file integrates wire-frame, surface and solid modelling by allowing these alternative representations of a solid to coexist naturally in an unified data structure (Spatial Technology, 1998). Most important is the fact that SAT files have an open format so that third part applications not based on AutoCAD can have access to the ACIS model. The structure of the SAT file has two basic components known as the geometry and Topology of the model.

Geometry refers to the physical items represented by the model (such as points, curves, and surfaces), independent of their spatial or topological relationship.

The elements of geometry used in ACIS include points (APOINT), composite curves (COMPCURV), analytic surfaces (CONE, SPHERE, PLANE, TORUS), interpolated curves (INTCURVES), analytic curves (ELLIPSE, STRAIGHT), spline surfaces (SPLINE), and mesh surfaces (MUSHSURF). The ACIS free-form geometry routines are based on non-uniform rational B-Splines (NURBS).

Topology describes how geometric entities are connected. The ACIS B-Rep of a model has a hierarchical decomposition of the model's topology into the following objects:

- **Body.** It is the highest level of model object. A body is a collection of lumps that have a common transform. It may be a wire body, a sheet body, or a solid model.

- **Lump.** It is a set of connected 1D, 2D, or 3D points in space that is disjointed from all other lumps. Shells bind the lumps.

- **Shell.** It is a set of connected faces and/or wires. It can bind the outside of a solid or an internal void (hollow).

- **Sub-shells.** Form a further decomposition of shells for internal efficiency purposes of the ACIS model.

- **Face.** A connected portion of a surface bound by one or more loops of edges. A face can be double-sided; in which case it is infinitely thin. It can also be single-sided, in which case the face normal vector points away from one side of the face, and solid material is present on the other side of the face.

- **Loop.** It is a connected portion of a face boundary, which is made up of a series of coedges. Generally, loops are closed, having no actual start or end point, but they may be open.

- **Wire.** It is a connected series of coedges that are not attached to a face.

- **Coedge.** Represents the use of an edge by a face or a wire.

- **Edge.** The topology associated with a curve. Vertices bind the edges.

- **Vertex.** A vertex bounds an edge. It is generally the corner of either a face or a wire. A vertex contains a reference to a geometric point in object space and to the edge or edges that it bounds. The other edges that meet at a given vertex can be found by following pointers through the coedges of the model.

SAT files are now being adopted by other solid modellers based on the ACIS technology, such as CADKEY, Mechanical Desktop, CATIA and Pro-Engineer, which gives a broader options of application of FEBAMAPP. SAT files are, in general, shorter than the DXF file for the same modelled part. The simplicity of integration of a text file like the SAT file into the FEBAMAPP system force the decision of using it as the by-directional exchange format between the solid modeller and FEBAMAPP application. Appendix 3 shows a sample SAT file.

6.3 Design of a Suitable Neural Network Architecture

Several references (Looney, 1993; Looney, 1996, Lankalapalli, et al, 1997, Chen and Lee, 1998, Onwubolu, 1999) pointed out from the beginning of the system development process that a multi-layer feed-forward network was the most appropriate NN architecture for the feature recognition problem stated in this research. But, as stated in Chapter 2, section 2.6.4 there are a few questions regarding the design and training of an NN that need to be solved by a trial-and-error approach.

One of the avenues explored, as part of the NN architecture design was the number of neural networks required to solve the recognition problem. On this matter, a first attempt for using a set of only two NN, to recognise the eight features object of this research, was made. To achieve this objective, it was required that each NN be able to recognise four (4) of the features plus a non-recognising feature output, which means that there were five (5) classes that needed to be recognised by the network. Following the recommendations given by Looney (1996), the number of neurons in the hidden-layer of the network was set to ten (10), which is two times the number of classes to be recognised. This initial architecture was created and a training attempt was made, which presented a long learning time and a lack of convergence in most cases.

The approach used to overcome the problem of convergence presented by the first architecture was to reduce the number of classes to be recognised by each NN. Therefore, the number of classes was set to two (2), which means that one (1) NN was necessary for recognising each feature. Following Looney's recommendations, then the number of neurons in the hidden-layer was reduced to four (4). This new architecture was successful in terms of convergence, meaning that each NN was able to recognise the feature it was trained to do. Also, the training time was dramatically reduced from more than one (1) hour in most cases to only a few minutes (7 minutes in the worst case).

6.4 The Inference Engine

The main requirement regarding the inference engine was that it had to be created in such a way that it were able to handle the different types of information and able to link the different modules of the FEBAMAPP system.

It was required that the system was able to read the SAT file and get the geometric and topologic information of the solid model. Also, the system needed to codify the model and use such a code as input to the NN system for feature recognition. Finally, the system needed to pass the information from the feature evaluation module back to the SAT file for display of the results in the original solid modeller used by the designer to create the model.

There was not an obvious decision about what programming language was the most suitable for such a complex task. Nevertheless, it was possible to identify a series of facilities that the programming language must have to facilitate the development of FEBAMAPP. Those facilities include those conventionally found in many high-level languages, such as declarable variables and arrays, data structures, control and data manipulation statements, file handling and so on. They also include statements for use of the system's user interface such as display of menus to the user or to interactively input data to the application.

Among the high-level languages able to satisfy the mentioned requirements are Fortran, Pascal, C and C++. Out of this options C++ is the most frequently used for graphic programming and as a matter of fact it is being used to develop AutoCAD and some other solid modellers. Also, the possibilities of using an expert system shell such as FLEX was studied, but the complications in transferring information between the different modules of FEBAMAPP made impossible to use it.

The familiarity of the researcher with C++ programming language also influences the decision of adopting it as the programming language for the development of FEBAMAPP. This research grant had a limited period of time; therefore reducing the overall time required for developing the application by reducing the necessary training of the researcher was crucial for the success of the project.

6.5 The Final System Framework

Figure 38 presents the framework of the Feature-Based Manufacturability Analysis of Plastics Parts (FEBAMAPP) system. The system evaluates the model starting with the pre-processing of the text file of the part (ACIS file), which is used in the automatic feature recognition module using a neural network system. This is followed by an evaluation of internal and external characteristics of all features identified and end up with a feedback to the designer in terms of design suggestions. Design suggestions are focused on those features, which may represent problems at manufacturing stage and they do not attempt to be general design suggestions for the whole model.

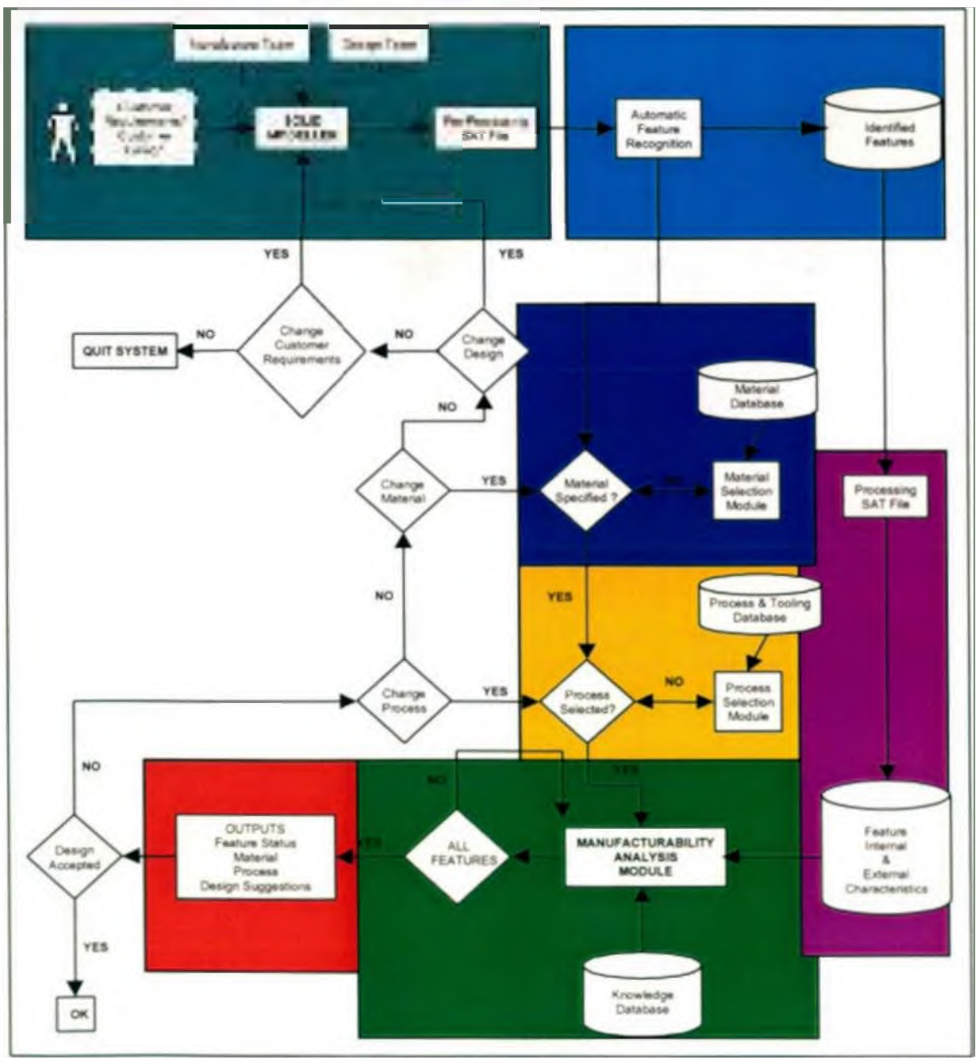


Figure 38. Framework of the FEBAMAPP system.

The product concept development process is rather complex in that requires a set of assumptions to simplify the task. The assumptions included in this system are that the market has been analysed, the need for a new product has been identified, design requirements and product constraints have been defined, and the functions of the mould reinforced parts or components have been identified based on design requirements and product constraints. The FEBAMAPP system focuses on evaluating proposed models at the early stage of the product development process using a rule-based expert system.

According to the human experts, the types of knowledge related to reinforced plastics manufacturing processes are usually represented in forms of equations, tables, rules of thumb and design constraints related to materials and/or processes. The frame-based representation method is used in FEBAMAPP to present the knowledge of each particular feature, while the rule-based knowledge representation is used to represent the decision logic and features mapping.

The declarative knowledge or facts used in FEBAMAPP can be broadly classified as follows:

- Feature knowledge (design constraints).
- Plastic material knowledge (plastic matrix).
- Reinforcing material knowledge (reinforcement fibre).
- Equipment and tooling knowledge (manufacturing processes).
- Design of mould components (knowledge and judgement).

The rules can be broadly categorised as follows.

- Rules for recognising features.
- Rules for material selection.
- Rules for process selection.
- Rules for evaluation of internal characteristics of features.
- Rules for evaluation of external characteristics of features.

FEBAMAPP uses the forward chaining instead of backward chaining based on the fact that forward chaining systems are used to solve problems oriented to data or diagnostic where the input facts are known and the user is looking for the derived output. Besides, forward chaining allows a simpler and better efficiency in execution.

The inference process begins with the information currently provided by the pre-processing of the SAT file of the solid model of the part and draws conclusions, according to the conditional rules that it knows already. During this process, it may request further details from the user such that proper selection of materials and manufacturing process can be used during the inference process. Eventually, it will arrive at logical consequences, which it then gives as its decision and a report in terms of design suggestions is generated.

6.5.1 The Prototype System

A prototype system has been developed as a Windows Application using Borland C++ according to the framework presented above and it consists of several modules as follows:

- Pre-processing of Sat file (PRESAT).
- Automatic feature recognition (AFR).
- Post-processing of the Sat file (POSTSAT).
- Material selection (MS).
- Process selection (PS).
- Manufacturability analysis (MA).
- Generate Report (GR).

The system is designed to run the modules in sequential order and modular reports of partial results from each module are available to the designer if required.

6.5.2 Program Structure

The source code of the program is distributed among several files. The file named *'feat5.h'*, contains classes and data transfer structure declarations used for handling and transferring data between the program functions. Also, there are two files with extension "*.cpp" called *'feature5.cpp'* and *'functs5.cpp'*, which contain the main function code and the member functions code of the program respectively.

By using object oriented programming techniques in the source code the *'main window'*, the *'child windows'*, the *'menu'*, and the *'dialog boxes'* are built. All these elements are called into the application by using identifiers saved *'feat5.rh'*, associated to the resource files *'feat5.h'* and *'feat5.rc'*, when they are required.

The sequence of using the main menu of the application is very important and it should follow a logic sequence associated to the manufacture procedures of reinforced plastic components. Such a sequence is given by:

- Indicate the SAT file to be processed by the FEBAMAPP system.
- Select the features to be identified. At this point the user may select either all features in the model or any particular combination of features available in the system.
- At this point the previously identified features are ready to be displayed and the user can choose between displaying all features or one feature at the time.
- It is intended that the manufacturability analysis performed by FEBAMAPP to be driven by the manufacturing process selected to produce the part. Therefore, the next step is to select the manufacturing process from the options available in the system.
- Next step involves selecting the intended materials to be used in the manufacturing of the part. The system store information related to several resins and reinforcements available in the market and the options for combination of such materials is constrained by the manufacturing process selected in the previous phase of the analysis process.
- Once features have been identified, and process and materials selected, the user is able to proceed to the evaluation of the features. Once more the user has the option to perform evaluation of all features identified in the model or perform evaluation of a specific type of feature or evaluation of a particular feature, which can be identified by its 'face tag' identifier.
- Finally, the model's manufacturability evaluation results are ready to be shown. There are two options available to show results of this evaluation. The first option is a text report including information about all features identified in the model plus its internals and externals characteristics evaluation. This option does not include by itself any graphical information of the model, but it can be used in combination with the intermediate SAT files generated by the application and displayed using any solid modeller capable of handling SAT files such as AutoCAD. The second option will

show evaluation results on the screen by using a combination of text information and a display of graphical feedback of the features. By using the "help" option available on this 'Results window' it is possible to obtain design recommendations related to the manufacturability difficulties found during the manufacturability analysis of the model.

Details about how to use all 'dialog boxes' and their available options are included in the sample run of the system shown in the next section.

6.6 Sample run

Sample part real1.sat, shown in Figure 39, will be used in the sample run of FEBAMAPP system to show how to use the system in performing manufacturability evaluation of a reinforced plastic modelled part.

The application must be open by running the executable file FEBA.exe from the directory where it had been installed. In this case it is installed in the FEBA directory in the C drive. Running "Feba.exe" file will open the main window of the application as it is shown in Figure 40.

The main window of the application has all capabilities of a traditional Windows applications program based on the objects oriented programming (OOP). It can be moved, sized, or hidden according to the user convenience. The main menu of this window offers to the user access to all manufacturability analysis options available in the application. Moreover, there is a logical sequence on calling the application functions, which must be followed to assure success of the model evaluation.

First, select the "SAT File" menu option from the main menu and then click on the 'proceed' option. Alternatively click in the icon located below the SAT File option of the main menu. Either option will open the *'Open SAT File'* dialog window, as it is shown in Figure 41. In the *'text box'*, next to the "SAT File name:" caption, type the name of the SAT file corresponding to the part to be analysed.

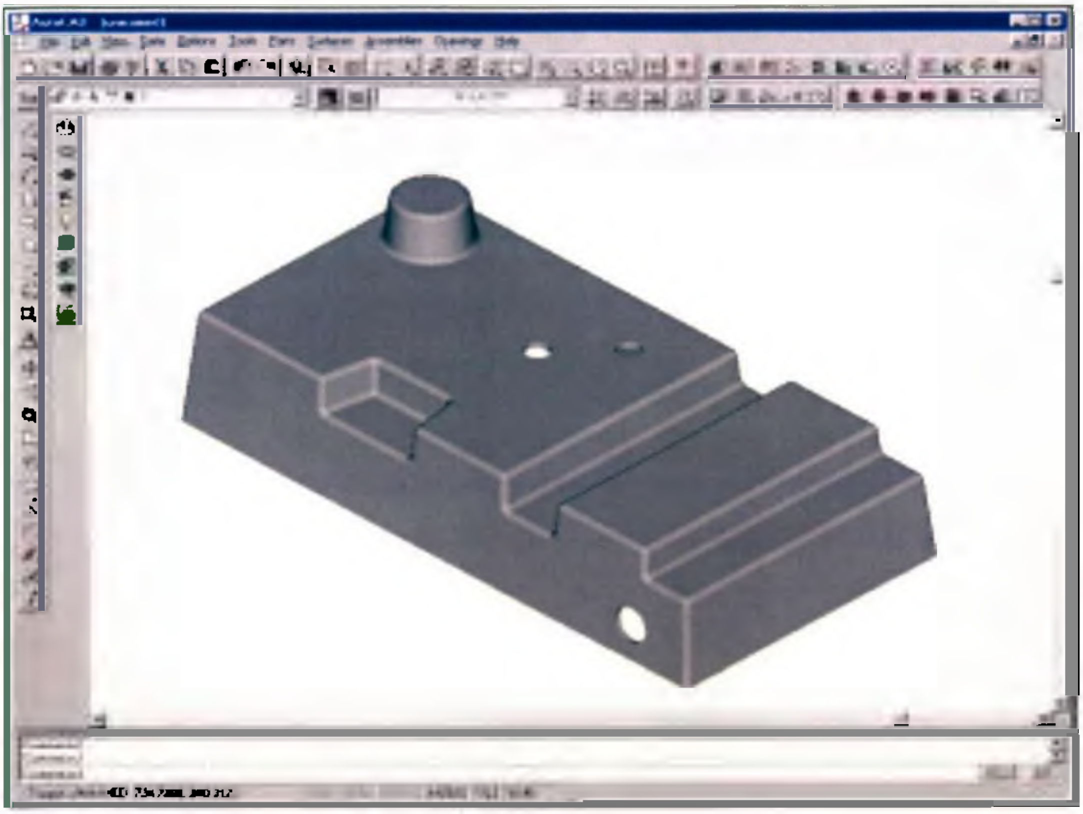


Figure 39. Real1.sat model to be used in the sample run of the system.

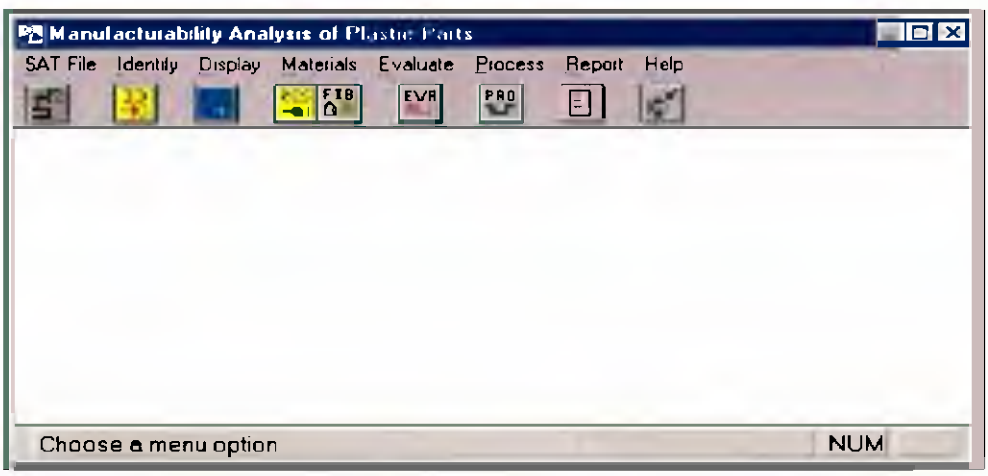


Figure 40. Main window of FEBAMAPP application.

The name of the file must be followed by its extension (*.sat), and then click on the "OK" button to proceed to the pre-processing of the Sat file. The "Cancel" option will close the application. Pre-processing the SAT file means transferring the solid model information stored in the SAT file to the data structures in the FEBAMAPP system. Data structures will be used in the following steps of the evaluation process.

Confirmation from the system that it had finished pre-processing the SAT file and all data structures had been created successfully is given in a message box as shown in Figure 42.

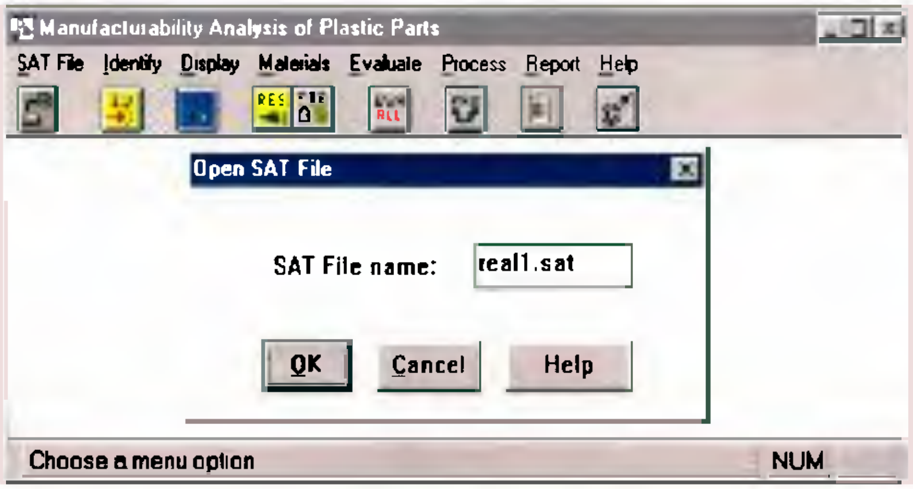


Figure 41. 'Open SAT File' dialog box.

Figure 42. Confirmation of pre-processing sat file successfully completed.

Now proceed to select the "Identify" option in the main menu. This menu option can also be activated by clicking on the icon located below the "Identify" option in the main menu, which will open the "Identify Features" dialog windows shown in Figure 43.

The options available in this dialog box allow the user to select the desired features to be identified in the model. "All Features" option as suggested by its name will perform an identification task, which will look in the model for all features the system was trained to identify. Also, the user is allowed to choose any particular combination of features from the available list to be identified in the model. The "All Features" option has priority over the list of features option, which means that if "All Features" is selected the features in the list are not available and to make them available then "All Features" must be inactivated.

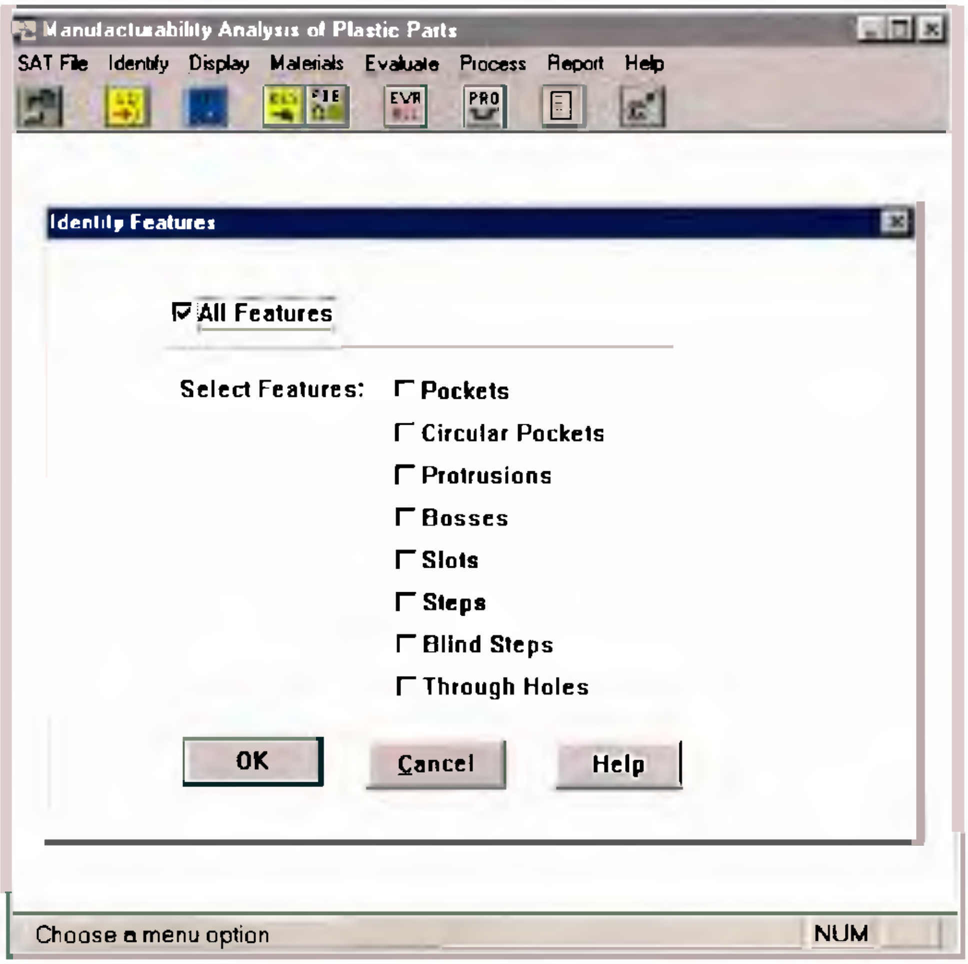


Figure 43. Identify Features dialog box.

The "OK" button will perform the identification of the features accordingly to the option selected by the user. The "Cancel" option will close the dialog box with a warning message telling the user that no identification option has been selected. The "Help" option will open a help file with information about the current dialog window and links to further information about the system, other dialog windows and commands available in the application.

At the end of the identification process a message box is generated by the system containing information about the features found in the model and their corresponding tag numbers to identify their main faces. Finally, there is a note advising the user that the identification matrix has been successfully built and he/she may proceed to the next stage of the analysis, as shown in Figure 44.

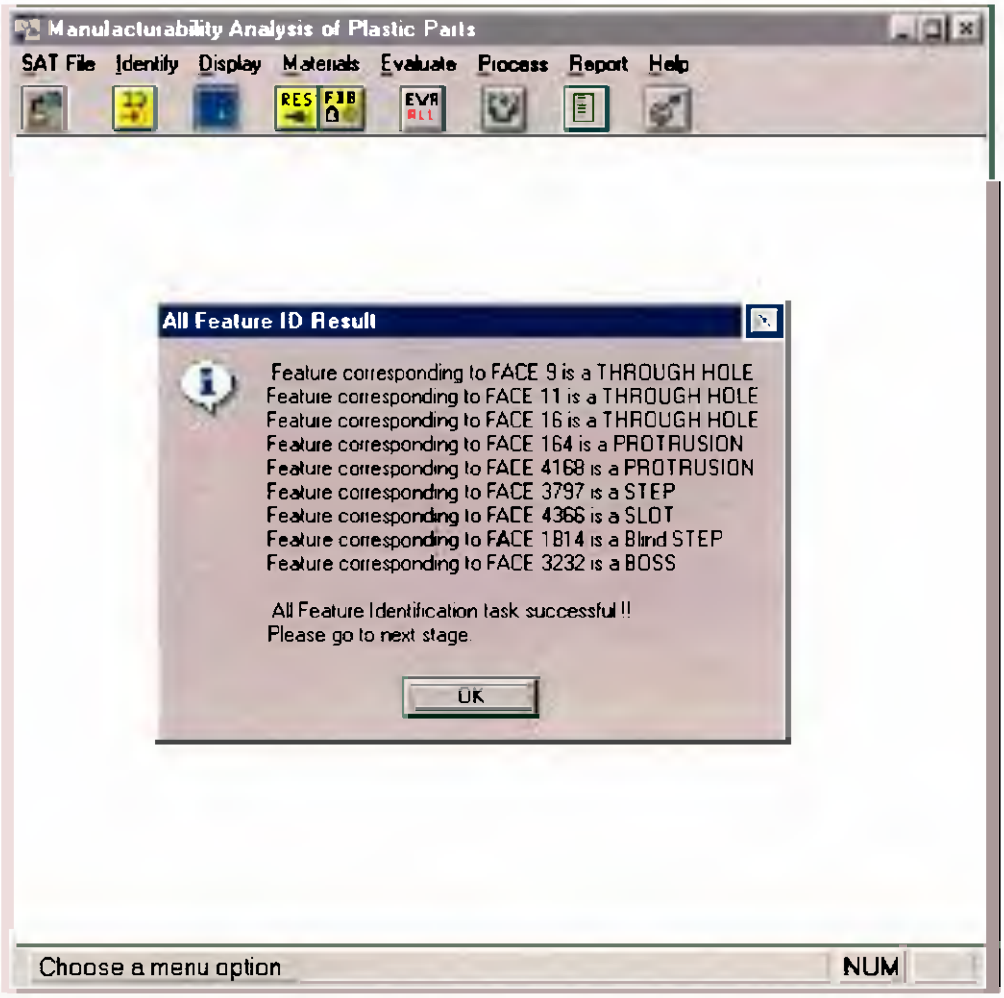


Figure 44. Confirmation of success in the feature identification task.

At this point the user may select the main menu option "Display" or the "Materials Selection". The first option will prepare all necessary SAT files for displaying the features accordingly to the selected option in the Display dialog box shown in Figure 45. The second option will open the "Materials Selection" dialog box. The actual display of the features for visual feedback of recognition and/or evaluation is made in the current application used by the user to create the original model of the part, Mechanical Desktop from Autodesk in the current application.

A new option is available in the "Display" dialog box, which allows the user to prepare a file to display a particular feature on the screen. In general the display of features will use a colour code corresponding to each type of feature as a manner of highlighting it from the rest of the model features or faces.

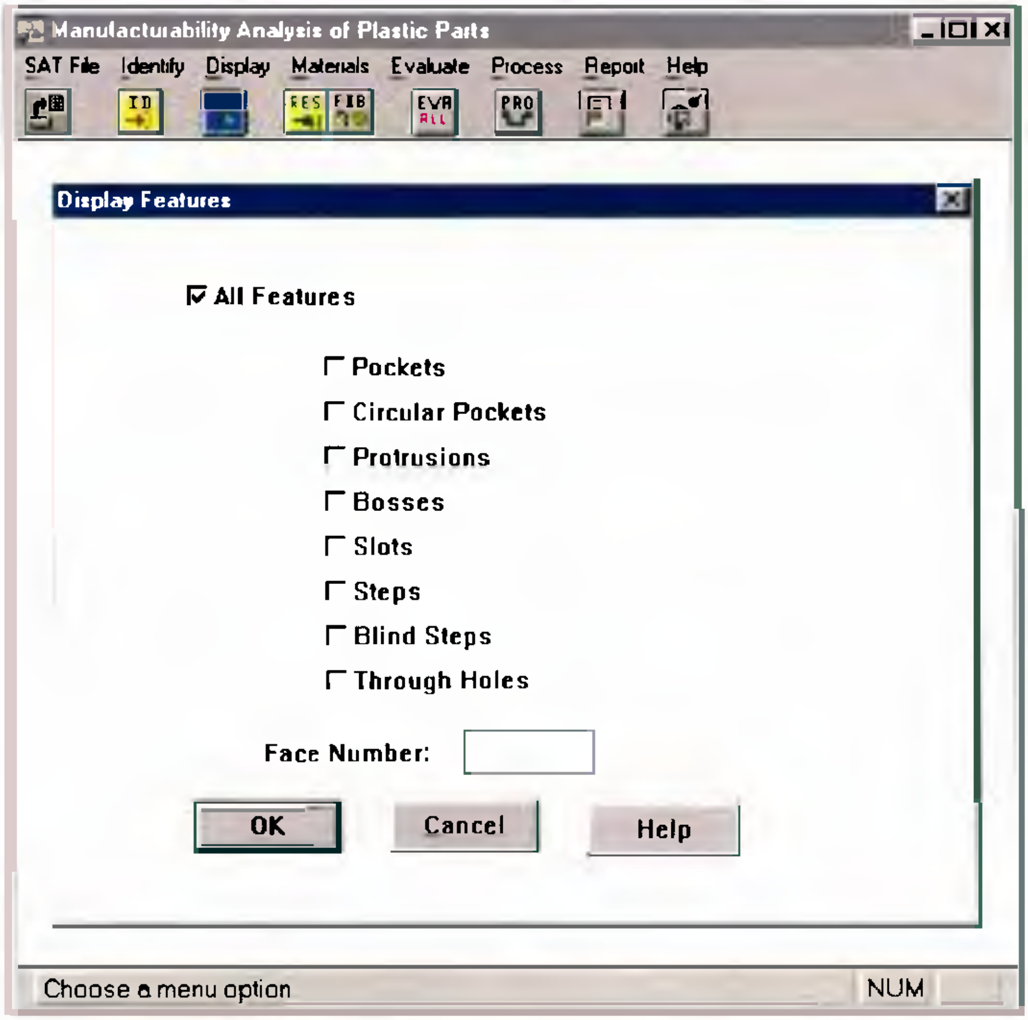


Figure 45. "Display Features" dialog box.

Figure 46 shows sample part real1.sat after the "Display" processing of the file using the "All Feature" option. It is possible to observe a total of 9 features identified using the feature colour code. The feature recognition module was used to identify these features and results were shown in Figure 41. The factor of confidence for the recognition of these features is not shown in the "Message Box" but it is available in the written report of the feature recognition and manufacturability evaluation of the model.

Threshold for recognition on the Neural Network System (NNS) was set to 0.9 (90%), during the training of the system, to reduce the training time required and also to avoid over-training allowing the NNS to generalise under the presence of unknown data. The confidence factor for identification of features in this particular example range between 93.2% for Slot, to 99.9% for Protrusion. The Boss and Blind Step features, used to highlight the manufacturability analysis of this sample part, were identified to a confidence value of 99.0% and 98.0% respectively.

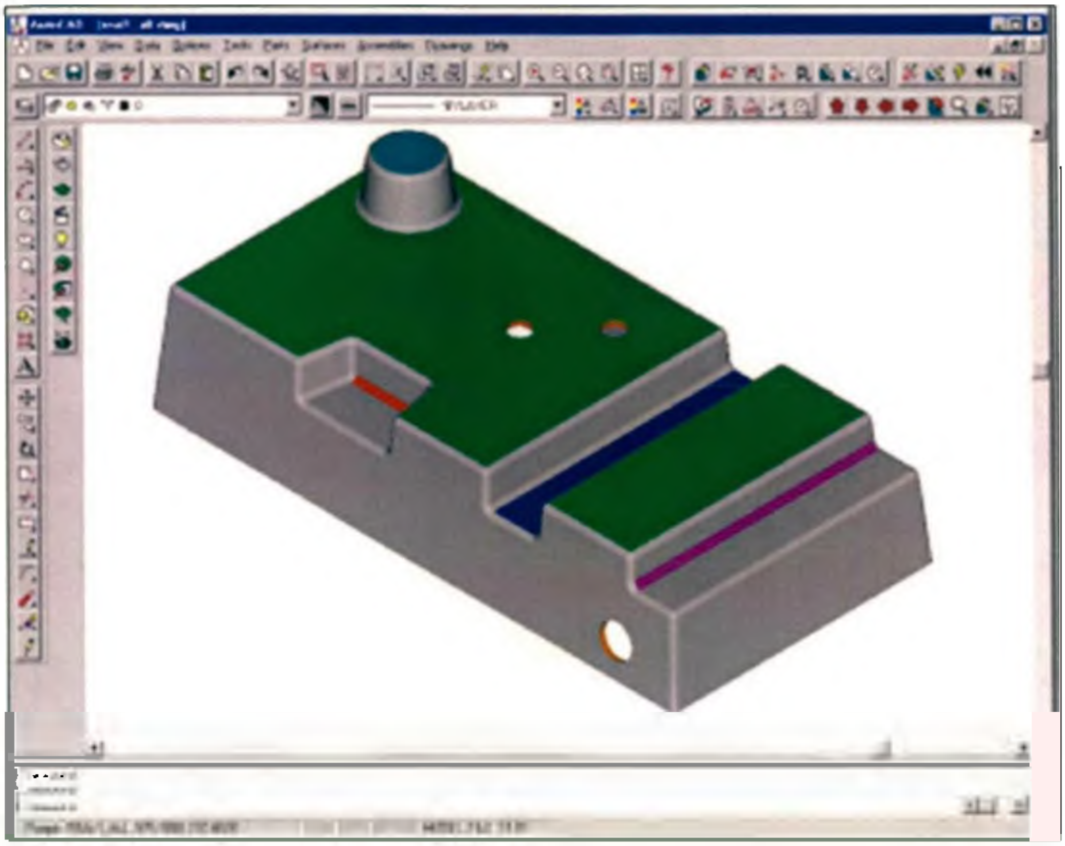


Figure 46. Visual display of the feature identification results.

As previously mentioned, after completion of the feature identification task, if the user chooses to carry on with the manufacturability analysis of the model then he/she must advance to the materials selection stage by clicking on the "Materials" option in the main menu. Also using the icons located below "Materials" in the main menu can activate this option. There are two icons available; the first one is used to open the dialog box corresponding to the selection of resins and the second icon for opening the dialog box corresponding to the reinforcement selection.

The "Resin Selection" dialog box shown in Figure 47 presents to the user the option of using thermosetting or thermoplastic resins for the analysis. The resin to be used will depend on the design requirements of the modelled part. Along with the resin available in the system, this dialog box also offers the user a "Help" button, which will open a help file containing advice and information regarding selection of resins for reinforced plastic applications. If the user selects no particular resin, then the default option (Polyester) will be used in further stages of the manufacturability analysis process.

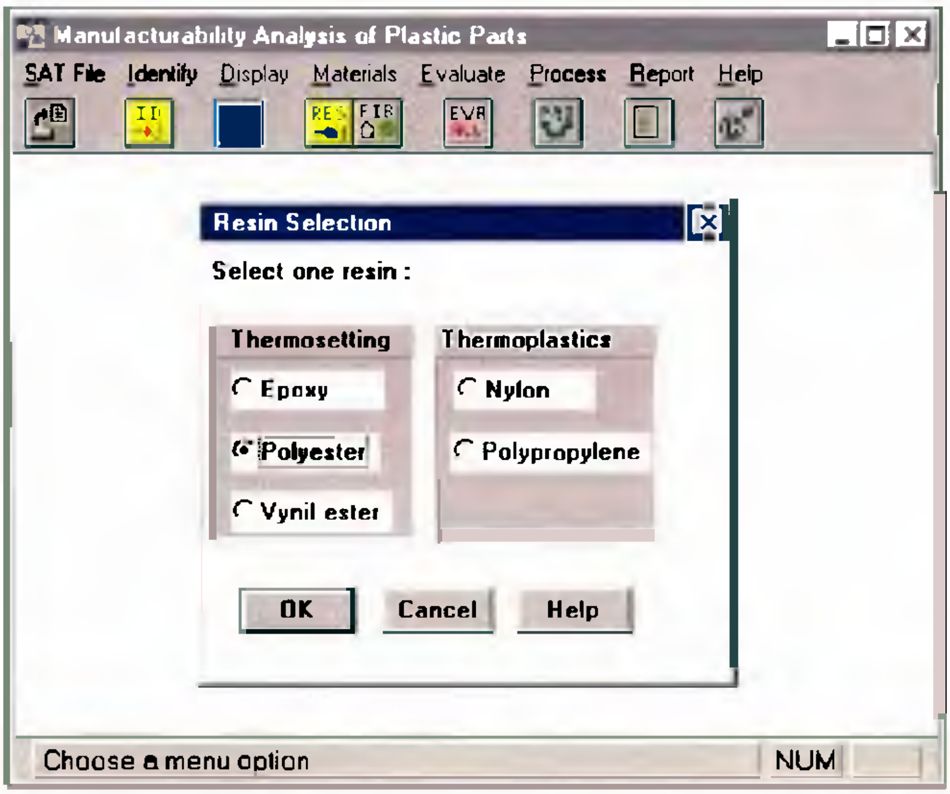


Figure 47. Resin Selection dialog box.

Next the user must select the kind of reinforcement to be used for the analysis. Figure 48 shows the reinforcement options available in the FEBAMAPP system, where the default option is to use E-Glass reinforcement fibres. Once more, FEBAMAPP presents the user with the "Help" button, which will open a help file with information regarding properties and applications of the fibres available in the system.

After selection of materials is complete, the next stage is to select the manufacturing process to be used during the manufacturability evaluation of the modelled part. It is known that design characteristics can be constrained upon the materials and manufacturing process intended to be used during the manufacture of the reinforced plastic components, therefore the appropriate combination of those elements is vital for the success of the final product's design.

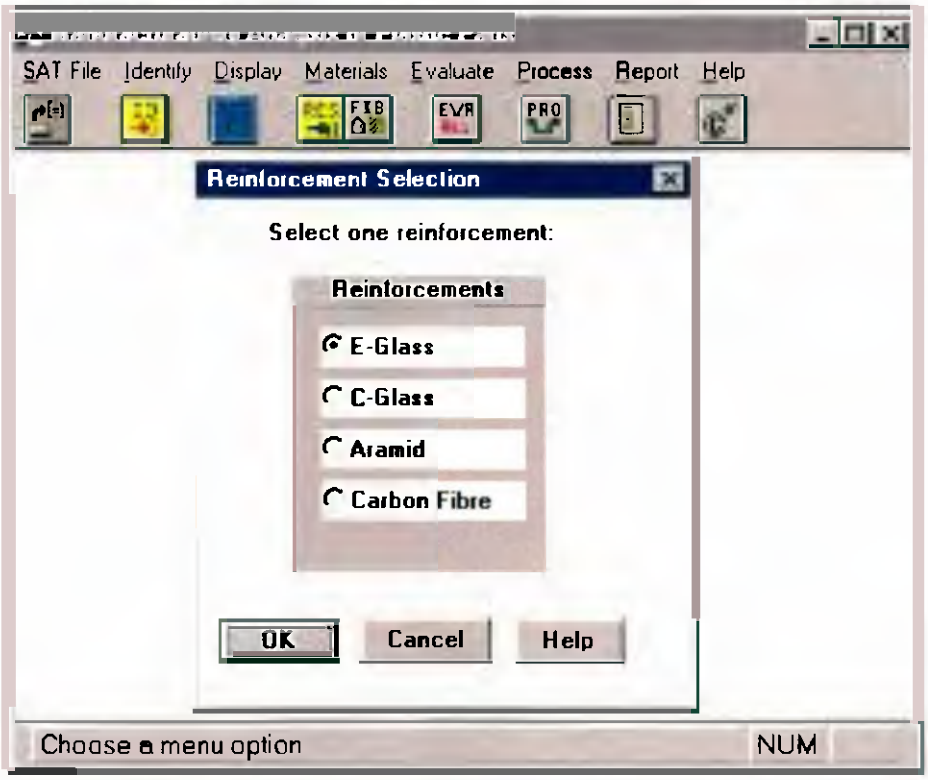


Figure 48. Reinforcement selection dialog box.

Figure 49 shows the "Process Selection" dialog box where it can be observed that "Hand Lay-up" is the default manufacturing process to be used in the analysis. The "Help" button will open a help file containing useful information about the manufacturing processes available in the system. Also, this help file will give some hints and suggestions to the designer about selection of appropriate manufacturing process based on the production rate required for a particular model and the materials to be used during manufacture.

Following the materials and process selection stage the evaluation of the model can be completed. This can be done by selecting the "Evaluate" option in the main menu of the application or by using the icon located below such menu option.

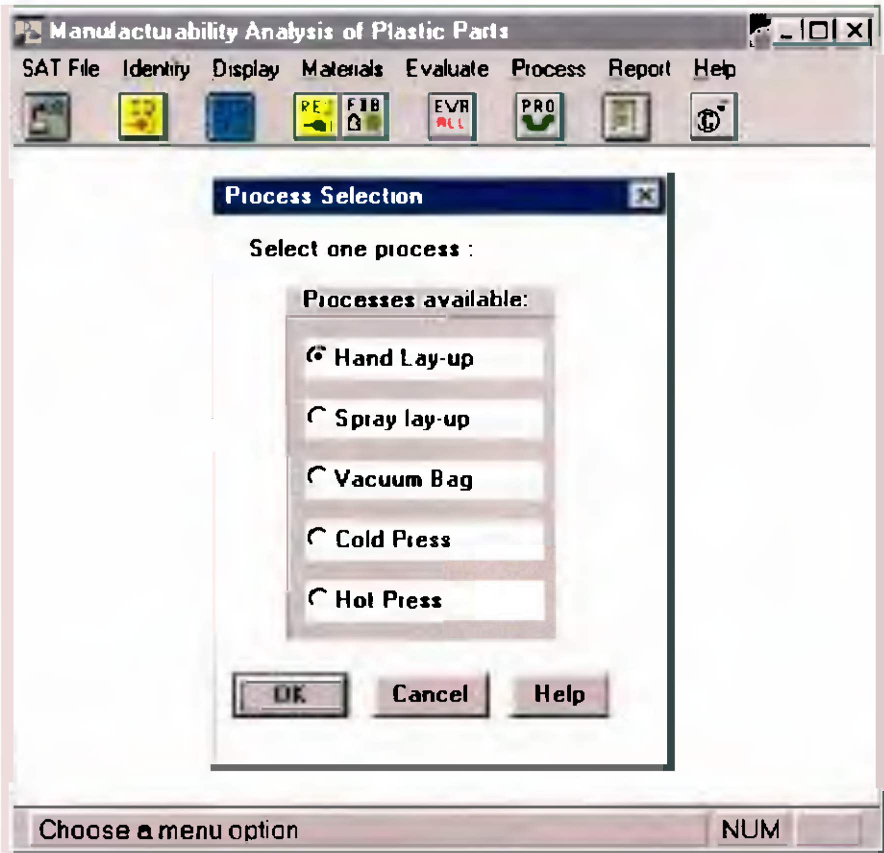


Figure 49. Process Selection dialog box.

Either one of them will open the "Evaluate Features" dialog box, where the user is presented with a set of options for evaluation of the model as can be seen in Figure 50. When "All Features" option is selected FEBAMAPP will present results using one Message box for each feature in the model in sequential order.

Figure 51 presents the result dialog box corresponding to the evaluation results of the Boss feature in the sample part Real1.sat. Results are presented using the face tag number identifying the feature, then the name of the variable being evaluated and its corresponding face tag number. Finally, the status of the variable as a result of comparing its actual value with the suggested values stored in the system database.

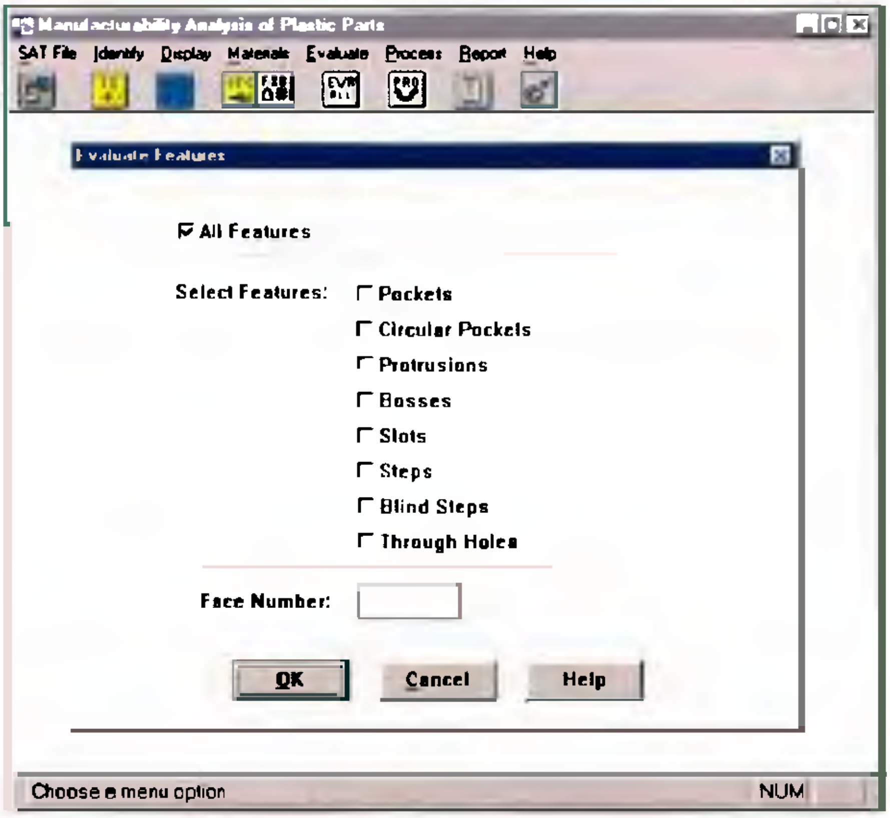


Figure 50. Evaluate Features dialog box.

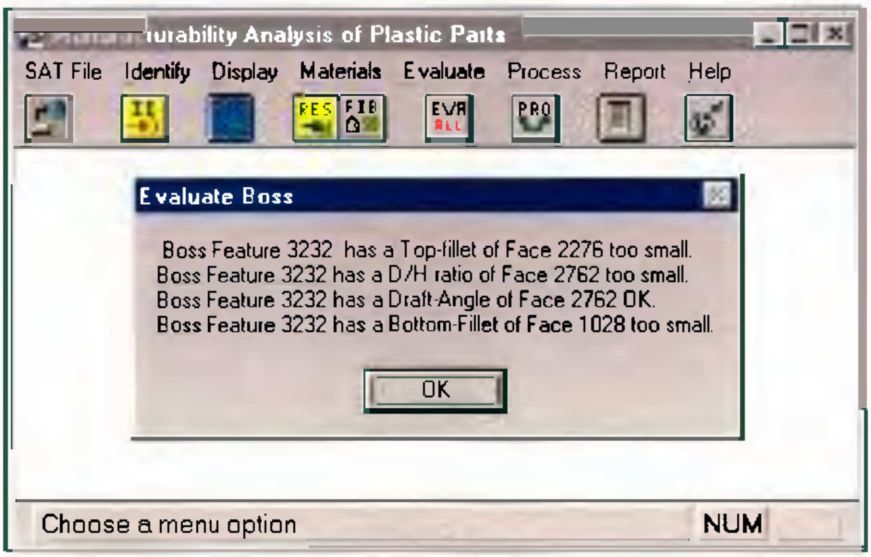


Figure 51. Result of the Boss feature evaluation.

At the same time that the message box with the results of the evaluation is presented on the screen, FEBAMAPP will also create an SAT file to graphically display the results of the evaluation using the original solid modeller. Red colour will be used for those faces in each feature that failed the evaluation, for instance the top fillet, draft angle and bottom fillet of the Boss feature in the sample part Real1.sat as shown in Figure 52.

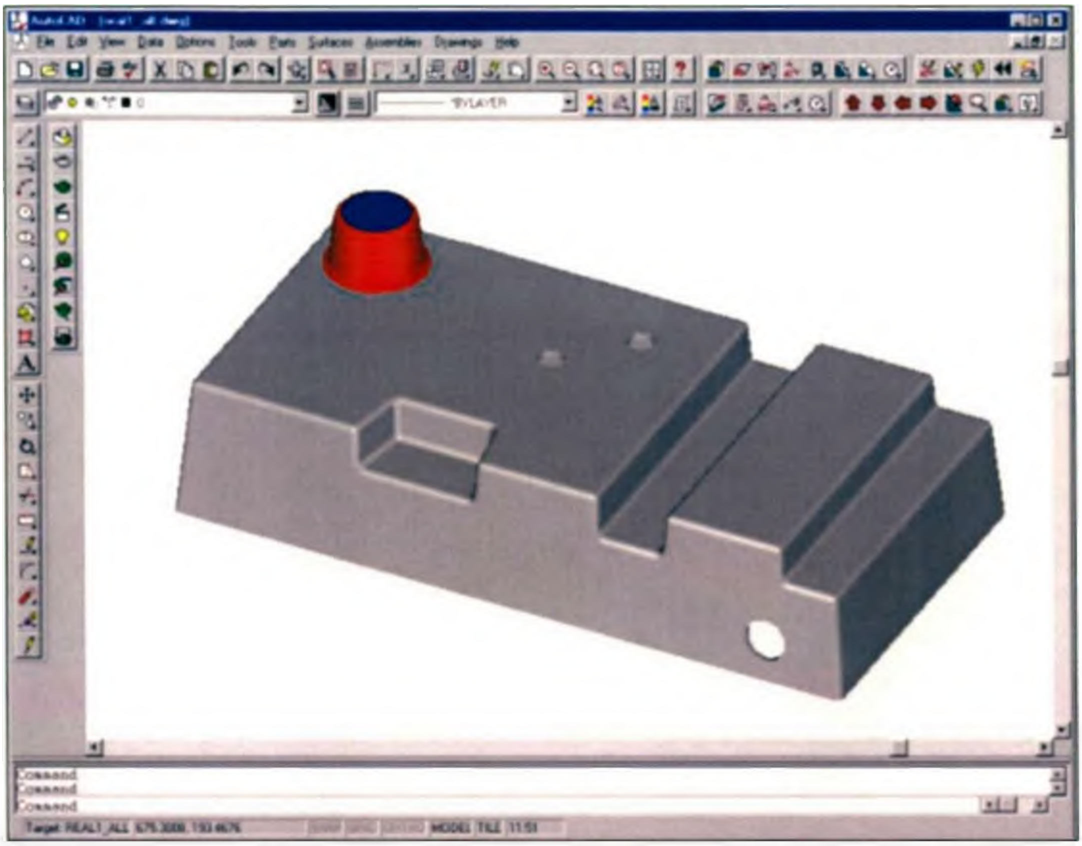


Figure 52. Graphical display of the evaluation results of the Boss feature in the sample part Real1.sat.

Each feature has particular characteristics that require checking. Basically the process consists of calculating or obtaining values of each characteristic and comparing those values against the target values stored in the database. The possible outputs from this checking process is, in the first place, that the feature characteristic is 'OK' which means that the particular dimension is acceptable according to the expert's recommendations. In the second place, the output could be 'Small', which represents a possible difficulty at manufacturing time, requiring some redesign of the part. A third option is that the variable value is 'Large', which for some features also may represent manufacturing inconveniences.

The same procedure as previously used for the evaluation of the Boss feature is followed for the evaluation of the Blind-Step feature. Also the same materials and manufacturing process are being used for the evaluation of this feature in the sample run of the system, therefore its corresponding materials selection dialog boxes will not be presented.

Figure 53 shows the dialog box with the evaluation results of the Blind-Step feature identified in the sample part Real1.sat. Once more, the pattern used for the results is used. Feature type, tag identification number of the face corresponding to the feature, variable being evaluated and tag number of the face corresponding to the variable, and finally the status of the variable.

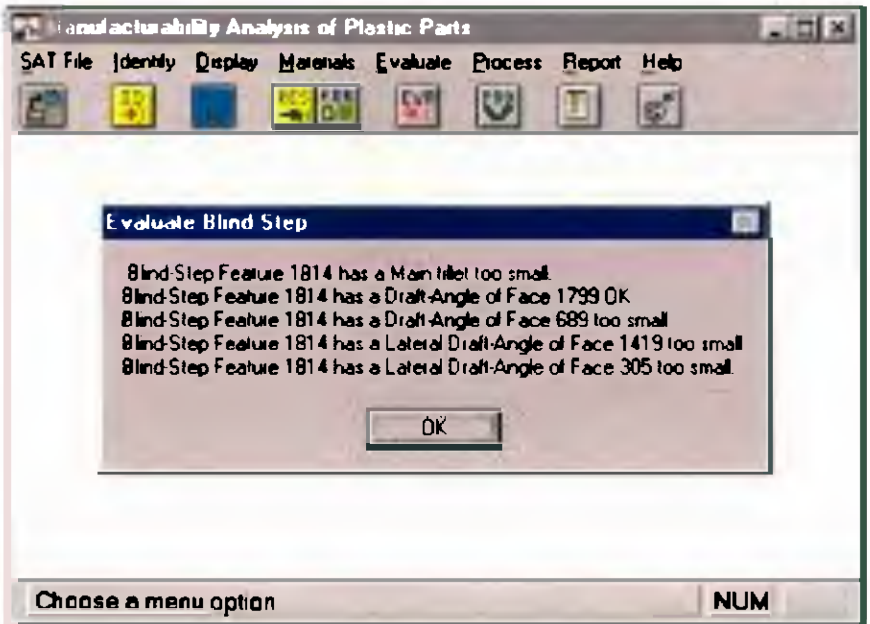


Figure 53. Result of the Blind-Step feature evaluation.

Also, a graphical display is created by FEBAMAPP and it can be used in conjunction with this "Message Box" and the text report of the evaluation of this sample part, which contains the full information of the model evaluation and feature characteristics. Figure 54 shows the graphical display of the evaluation corresponding to the Blind Step feature in sample part Real1.sat. As usual red colour is used to identify those faces corresponding to features that fail to pass the evaluation.

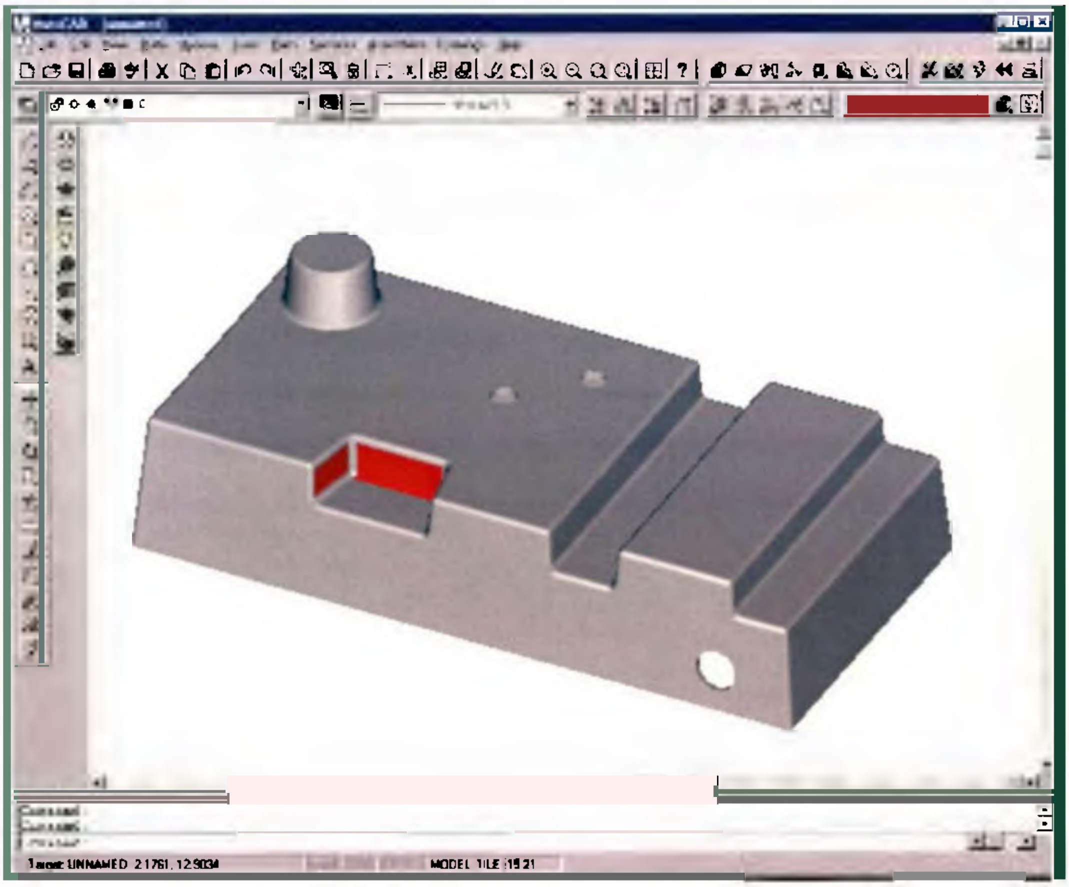


Figure 54. Graphical display of the evaluation results of the Blind Step feature in the sample part Real1.sat.

Evaluation results of the internal characteristics of Boss and Blind-Step features in Real1.sat sample part are resumed in Table 10 and the corresponding evaluation of external characteristics in Table 11.

The final step in the analysis process is to create a text report of the results. Selecting the main menu option "Report" will open the "Report" dialog box, as shown in Figure 55. Actually we had been using the "Screen Report" option as the default option, which presents immediate results on the screen as soon as the calculations are finished. The text report will create a text file called "Feature.out" and save it in the FEBAMAPP directory containing all the modelled part information and the results of the feature recognition and manufacturability analysis. A full text report of Real1.sat sample part is presented in Appendix 4.

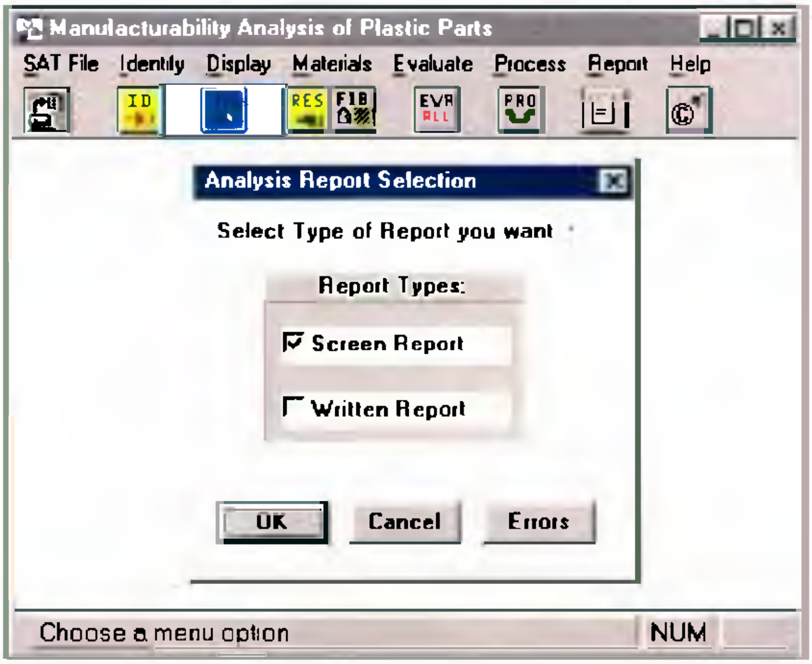


Figure 55. 'Report' Dialog Box.

Table 10. Evaluation of internal characteristics of features in sample part 1.

FEATURE	INTERNAL CHARACTERISTIC	ACTUAL VALUES	TARGET		STATUS	
			Hand lay-up	Pressure-Bag	Hand lay-up	Pressure-Bag
BOSS	Top-fillet	4	6.4	12.5	Small	Small
	Bottom-fillet	4	6.4	12.5	Small	Small
	Diameter	30	-	-	-	-
	High	35	25	-	-	-
	D/H	0.86	2.5	1.5	Small	Small
	Draft - angle	5	2	6	OK	Small
BLIND -STEP	Main fillet	4	6.4	12.5	Small	Small
	Lat. Draft angle 1	5	2	6	OK	Small
	Lat. Draft angle 2	5	2	6	OK	Small
	Main Draft angle	5	2	6	OK	Small

Table 11. Evaluation of external characteristics of features in sample part 1.

FEATURE	EXTERNAL CHARACTERISTIC	ACTUAL VALUES	TARGET		STATUS	
			Hand lay-up	Pressure-Bag	Hand lay-up	Pressure-Bag
BOSS	Distance to adjacent feature	35.0	25.0	20.0	OK	OK
	Distance to a border	30.0	25.0	20.0	OK	OK
BLIND -STEP	Distance to adjacent feature	40.0	30.0	20.0	OK	OK
	Distance to a border	45.0	25.0	20.0	OK	OK

Also the user has access to information regarding the design errors found in the modelled part and the manufacturing implications that they may have in the product development process. The "Errors" option in the "Report" main menu option will open a help file with the information concerning the design errors found during the evaluation of the model, as shown in Figure 56.

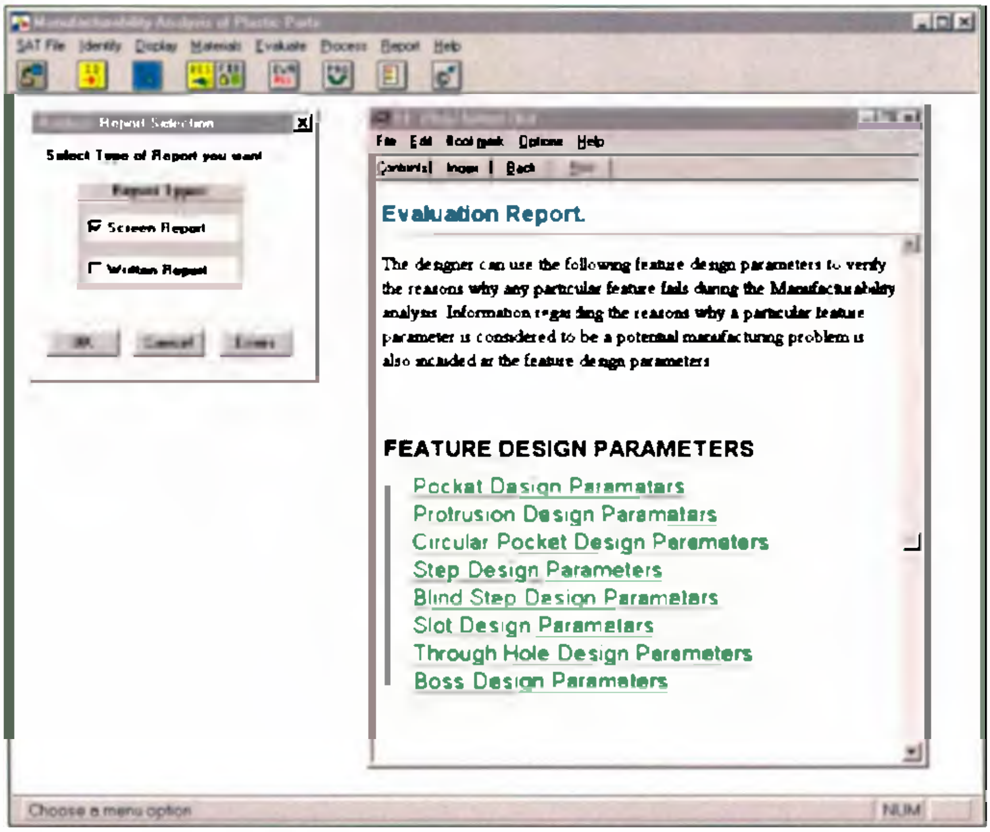


Figure 56. Help display of the evaluation report.

Chapter 7

7 RESULTS AND DISSCUSION OF RESULTS

7.1 Results

This chapter will present results from different sample parts used to show the performance of FEBAMAPP regarding the feature identification task as well as the feature evaluation.

The expert at Pearl GRP was confronted with typical orthogonal views of the sample parts, where he identified the main features that might represent potential threats for the manufacturing of the proposed design. Also, the expert was asked to evaluate those features that he identified in the previous stage, in terms of manufacturability of the model.

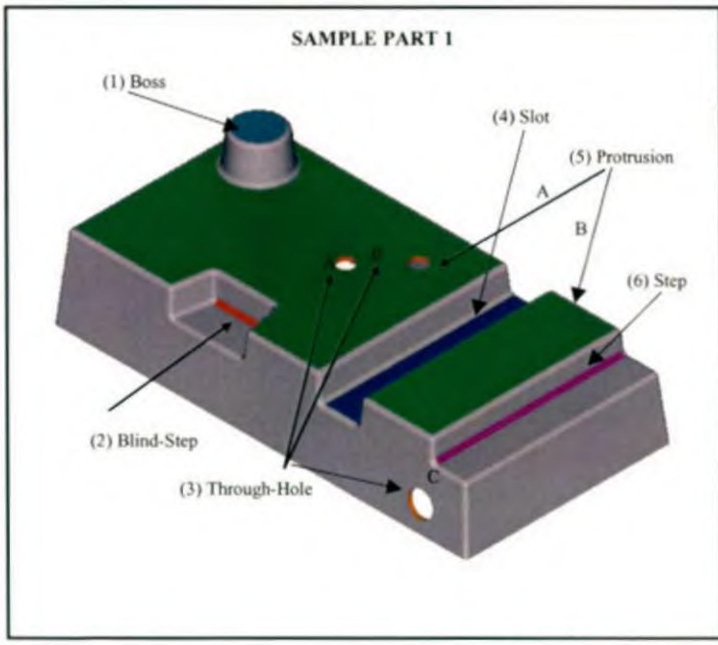
This chapter will also illustrate the comparison between the results obtained using FEBAMAPP and those results given by the expert evaluation of the sample parts in terms of manufacturability and evaluation time.

The results are presented in terms of factor of confidence for feature recognition when using FEBAMAPP and status of the variables being evaluated as part of the manufacturability analysis. Also information is included regarding the time required completing the recognition and evaluation of each feature in the sample parts by both, FEBAMAPP and the expert. Finally, results of the manufacturability analysis performed by the manufacturing expert in Pearl GRP Industries LTD are presented in this chapter.

7.1.1 Sample part 1

Real1.sat is used as the first sample-part, which has 166 faces and includes nine (9) features. Figure 57 shows results of feature recognition including the recognition confidence factors for each one of the features identified in the model by FEBAMAPP. It was assumed that Spray Lay-up would be used for manufacturing the part.

Next, there is a transcription of the file FeatID.out, which contains results of the feature recognition and feature evaluation corresponding to the sample part number 1 being evaluated. This is a standard text file created by FEBAMAPP's Results module as part of the evaluation feedback facilities of the system. Since the file is too long to be completely displayed in this section, then faces not relevant to the identification and evaluation of features have been deleted from the original file.



FEATURE	Recognition confidence factor
Boss	[0.98012]
Blind-Step	[0.97636]
Through Hole A	[0.99209]
Through Hole B	[0.98553]
Through Hole C	[0.95733]
Slot	[0.95675]
Protrusion A	[0.98312]
Protrusion B	[0.98663]
Step	[0.93641]

Figure 57. Feature identification results of sample part 1.

FEATURE IDENTIFICATION RESULTS

Potential Feature Matrix
Confidence Factors

Face	Pock	Step	Boss	Prot	Slot	Thol	Cpck	Bstp
9	1.2e-11	1.4e-07	2.5e-06	2e-15	4.3e-13	0.99	0.00013	8.9e-13
11	1.2e-11	1.5e-07	6e-07	2.3e-15	1.1e-14	0.99	0.00023	7.1e-13
16	1.2e-11	1.5e-07	6e-07	2.3e-15	1.1e-14	0.96	0.00023	7.1e-13

164	1.2e-11	0.00019	0.0002	**0.98**	0.0032	0.00033	0.2	4.5e-13
4168	1.2e-11	2.7e-05	5.9e-05	**0.99**	3.2e-07	5.3e-07	6.3e-06	3.9e-13
3797	1.2e-11	**0.94**	4.5e-11	1.8e-15	2.6e-10	0.0096	0.0036	1.1e-12
4366	1.2e-11	1.1e-07	0.00015	1.5e-15	**0.96**	4.8e-11	1.1e-06	1.0e-12
1814	1.5e-10	2.4e-08	5.8e-05	1.5e-15	3.1e-05	4.8e-12	0.00096	**0.98**
3232	1.2e-11	5e-08	**0.98**	1.5e-15	6.6e-16	9.8e-11	8.9e-06	3.5e-13

FEATURE IDENTIFICATION REPORT
Feature corresponding to **FACE 9** is a **T_HOLE**

Feature corresponding to **FACE 11** is a **T_HOLE**

Feature corresponding to **FACE 16** is a **T_HOLE**

Feature corresponding to **FACE 164** is a **PROTRUSION**

Feature corresponding to **FACE 4168** is a **PROTRUSION**

Feature corresponding to **FACE 3797** is a **STEP**

Feature corresponding to **FACE 4366** is a **SLOT**

Feature corresponding to **FACE 1814** is a **B_STEP**

Feature corresponding to **FACE 3232** is a **BOSS**

FEATURE EVALUATION REPORT
T Hole Feature 9 requires special moulding process.
T Hole Feature 9 can be moulded in the part
T Hole Feature 9 has a cylinder angle that needs to be aligned to Z-axis

T_Hole Feature 11 can be moulded in the part
T_Hole Feature 11 has a Draft-Angle of Face 164 OK.

T_Hole Feature 16 can be moulded in the part
T_Hole Feature 16 has a Draft-Angle of Face 164 OK.

Protrusion Feature 164 has a Top-fillet of Face 1824 too small
Protrusion Feature 164 has a Top-fillet of Face 1393 too small
Protrusion Feature 164 has a Top-fillet of Face 932 too small
Protrusion Feature 164 has a Top-fillet of Face 560 too small
Protrusion Feature 164 has a Draft-Angle of Face 1944 too small
Protrusion Feature 164 has a Draft-Angle of Face 1937 too small
Protrusion Feature 164 has a Draft-Angle of Face 2311 OK
Protrusion Feature 164 has a Draft-Angle of Face 118 too small
Protrusion Feature 164 Bottom-Fillet: Fillet of Face 1944 does not exist
Protrusion Feature 164 Bottom-Fillet: Fillet of Face 1937 does not exist
Protrusion Feature 164 has a Bottom-Fillet of Face 3676 too small
Protrusion Feature 164 Bottom-Fillet: Fillet of Face 118 does not exist

Protrusion Feature 4168 has a Top-fillet of Face 4258 too small
Protrusion Feature 4168 has a Top-fillet of Face 4003 too small
Protrusion Feature 4168 has a Top-fillet of Face 3607 too small
Protrusion Feature 4168 has a Top-fillet of Face 3455 too small
Protrusion Feature 4168 has a Draft-Angle of Face 4243 OK
Protrusion Feature 4168 has a Draft-Angle of Face 4175 OK
Protrusion Feature 4168 has a Draft-Angle of Face 1937 too small
Protrusion Feature 4168 has a Draft-Angle of Face 118 too small
Protrusion Feature 4168 has a Bottom-Fillet of Face 4540 too small
Protrusion Feature 4168 has a Bottom-Fillet of Face 3797 too small

Protrusion Feature 4168 Bottom-Fillet: Fillet of Face 1937 does not exist
Protrusion Feature 4168 Bottom-Fillet: Fillet of Face 118 does not exist

Step Feature 3797 has a Main-fillet too small
Step Feature 3797 has a Draft-Angle of Face 4175 too small
Step Feature 3797 has a Draft-Angle of Face 1958 OK.
Step Feature 3797 has an external fillet of Face4003 too small.
Step Feature 3797 has an external fillet of Face767 too small.

Slot Feature 4366 has a bottom-fillet of face 3888 too small.
Slot Feature 4366 has a bottom-fillet of face 3210 too small.
Slot Feature 4366 has a bottom-fillet of face 4540 too small.
Slot Feature 4366 has a bottom-fillet of face 3676 too small.
Slot Feature 4366 has a Draft-Angle of Face 1937 too small
Slot Feature 4366 has a Draft-Angle of Face 118 too small
Slot Feature 4366 has a Draft-Angle of Face 4243 OK
Slot Feature 4366 has a Draft-Angle of Face 2311 OK
Slot Feature 4366 Top-Fillet: Fillet of Face 1937 does not exist
Slot Feature 4366 Top-Fillet: Fillet of Face 118 does not exist
Slot Feature 4366 has a Top-Fillet of Face 4258 too small
Slot Feature 4366 has a Top-Fillet of Face 932 too small

Blind-Step Feature 1814 has a Main-fillet too small
Blind-Step Feature 1814 has a Draft-Angle of Face 1799 OK
Blind-Step Feature 1814 has a Draft-Angle of Face 689 too small
Blind-Step Feature 1814 has a Lateral Draft-Angle of Face 1419 too small.
Blind-Step Feature 1814 has a Lateral Draft-Angle of Face 305 too small.

Boss Feature 3232 has a Top-Fillet of Face 2276 too small.
Boss Feature 3232 has a D/H ratio of Face 2762 too small.
Boss Feature 3232 has a Draft-Angle of Face 2762 OK
Boss Feature 3232 has a Bottom-Fillet of Face 1028 too small
END OF FILE

Regarding the FEBAMAPP's processing time for each stage of the recognition and evaluation process the results for sample part 1 are as follows:

Pre-processing including feature identification: 24 sec/all features.

Preparation of Identification Display files: 51 sec/all features

Evaluation including Display files: 26-sec/each features, average.

Figure 58 shows the SAT files created by FEBAMAPP as part of the feature evaluation process to display the results in the modeller used by the designer to create the model of the part. Red colour faces are used to highlight those faces that fail to pass the evaluation and they are in agreement with the results shown in the output text file FeatID.out. There is one SAT file for each feature being considered for evaluation and they can be displayed individually or in a group as it is displayed here.

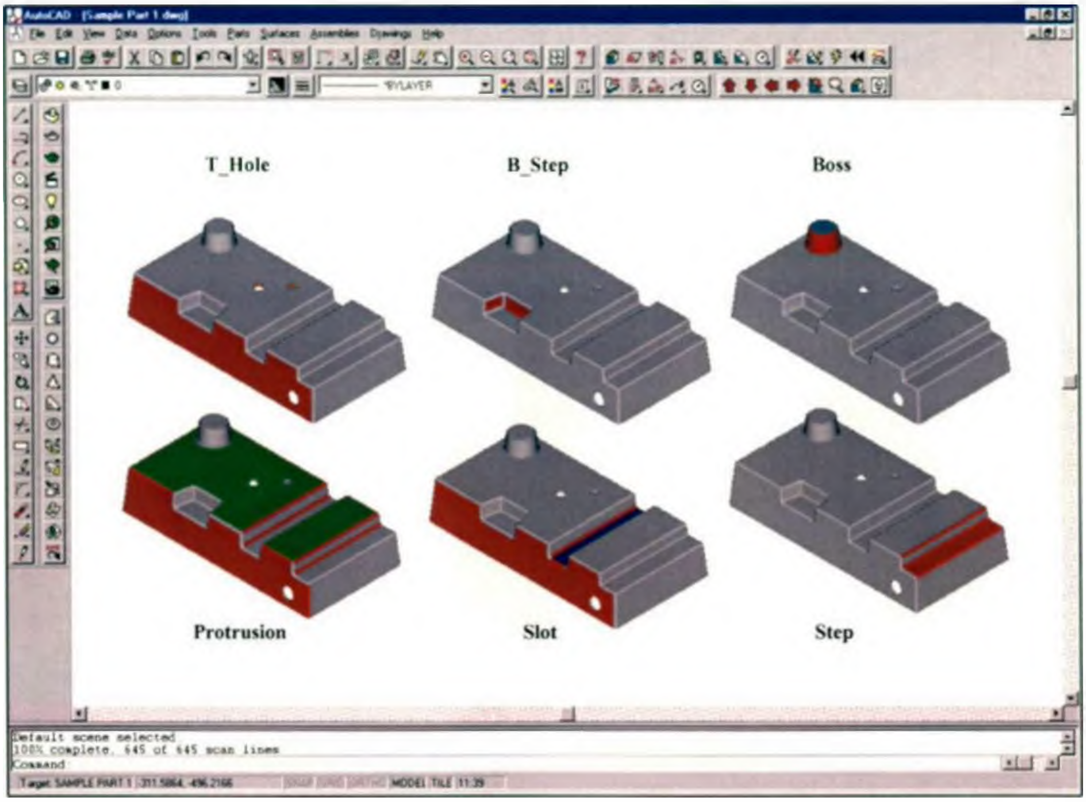


Figure 58. FEBAMAPP manufacturability evaluation results of sample part 1.

Regarding the identification of the features, there was a complete agreement with the features identified by the expert and those identified by FEBAMAPP, which means that FEBAMAPP was able to identify 100% of the features present in the model. FEBAMAPP achieved the recognition task with a recognition confidence factor ranging between 93% and 99% as it is shown in Figure 57. The expert's time required for feature identification was only a minute, which does not represent a big difference with the performance of FEBAMAPP that uses 24 seconds to recognise the features in this sample part. Therefore, it is possible to say that the recognition results from FEBAMAPP are as expected for sample part1.

The results from the evaluation performed by the expert can be resumed as follows:

- In general terms all fillets used in the part were not in concord with the recommended values for the manufacturing process selected, which according to the expert must be as large as possible and should not have less than 6.0 to 8.0 mm.

- Also, in the first instance of the evaluation a comment in reference to the draft angles used and the expert raised the doubt about their correctness. After a close check of the information given in the orthogonal views of the part, a definitive judgement was given in reference to this variable with the argument that they were too small in relation to the dimensions of the part and the manufacturing process selected.

- The Boss feature was considered too tall in relation to the diameter of the cone. Recommendation was given as to increase the diameter of the boss or decrease its length such that a proper tool gap for laying and rolling the material during production would be given. There was no objection regarding the position of the Boss feature in relation to the other features in the part.

- Regarding the evaluation of the Blind-Step, Slot, Step and Protrusion features, according to the expert, they did not present problems beside the fact that the fillets and draft angles were too small as pointed before.

- Finally, no problems were found related to the Through-Hole features A and B. There was suggested to drill them after curing of the part as to reduce complexities of the moulding process. Almost the same result was obtained from the analysis of Through_Hole C. It was also pointed out that if this type of moulding were required, then special moulding procedures would be necessary to facilitate the de-moulding process because it was not aligned to the Z-axis.

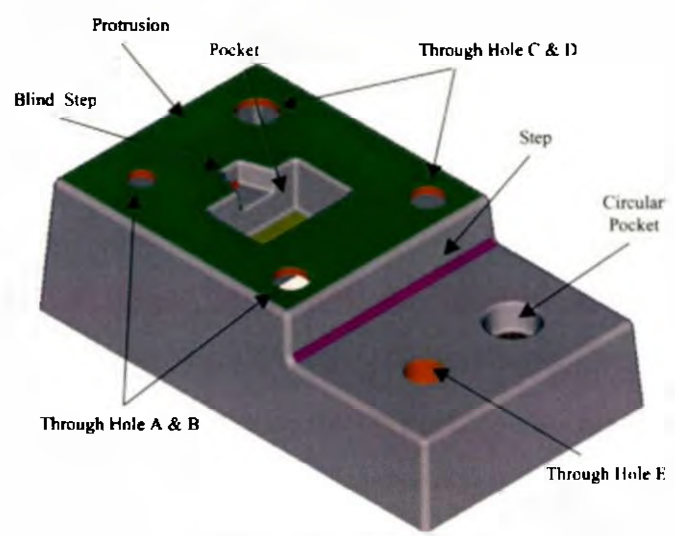
Evaluation results from FEBAMAPP are as expected for sample part 1, and they are shown in the Features Evaluation Report. The time required by the expert to perform the manufacturability analysis of this part was slightly over 15 minutes, which is approximately 7 times greater than the time used by FEBAMAPP to perform the evaluation to the same sample part.

FEBAMAPP creates, simultaneously, a text file and a graphic-display file where all results from the evaluation are available for future reference by the designer and/or manufacturer. If the expert were asked to write a report about his evaluation of the part, then it would take considerably longer to complete the evaluation/report process.

7.1.2 Sample part 2

Sample part 2 has been used by other authors in reporting feature recognition results of different algorithms. Modifications were introduced in the original part to transform it into a hollow part to be produced using reinforced plastics manufacturing processes. This particular sample part has 171 faces and 10 features. Figure 59 shows results of the feature recognition performed by FEBAMAPP. Results obtained from FEBAMAPP will be compared with results from other authors in the Discussion of Results section.

SAMPLE PART 2



FEATURE	Recognition confidence factor
Blind-Step	[0.98103]
Through Hole A	[0.99203]
Through Hole B	[0.97904]
Through Hole C	[0.97904]
Through Hole D	[0.97904]
Through Hole E	[0.97904]
Protrusion	[0.99034]
Step	[0.97980]
Circular Pocket	[0.99790]
Pocket	[0.98190]

Figure 59. Feature identification results of sample part 2.

FEATURE IDENTIFICATION RESULTS

Potential Feature Matrix
Confidence Factors

Face	Pock	Step	Boss	Prot	Slot	Thol	Cpck	Bstp
38	1.2e-11	6.1e-07	9.5e-19	7.1e-13	2.9e-07	8.2e-06	1.0	4e-13
513	1.2e-11	0.0003	0.00047	**0.99**	0.00063	0.00082	0.37	4.7e-13
264	1.2e-11	**0.98**	2.2e-11	1.6e-15	3.4e-10	0.00011	0.00032	1.3e-12
3070	1.5e-10	2.4e-08	5.8e-05	1.5e-15	3.1e-05	4.8e-12	0.00096	**0.98**
3164	**0.98**	1.7e-08	1.6e-13	1.5e-15	1.2e-15	5.2e-10	0.0023	3.5e-13
174	1.2e-11	1.7e-07	5.4e-07	1.7e-15	8.5e-05	**0.99**	0.00015	2.5e-12
817	1.2e-11	1.8e-07	6e-08	2.6e-15	3.1e-15	**0.98**	0.00046	6.1e-13
969	1.2e-11	1.8e-07	6e-08	2.6e-15	3.1e-15	**0.98**	0.00046	6.1e-13
1154	1.2e-11	1.8e-07	6e-08	2.6e-15	3.1e-15	**0.98**	0.00046	6.1e-13
1392	1.2e-11	1.8e-07	6e-08	2.6e-15	3.1e-15	**0.98**	0.00046	6.1e-13

FEATURE IDENTIFICATION REPORT

Feature corresponding to **FACE 38** is a **C_POCKET**
Feature corresponding to **FACE 513** is a **PROTRUSION**
Feature corresponding to **FACE 264** is a **STEP**
Feature corresponding to **FACE 3070** is a **B_STEP**
Feature corresponding to **FACE 3164** is a **POCKET**
Feature corresponding to **FACE 174** is a **T_HOLE**
Feature corresponding to **FACE 817** is a **T_HOLE**
Feature corresponding to **FACE 969** is a **T_HOLE**
Feature corresponding to **FACE 1154** is a **T_HOLE**
Feature corresponding to **FACE 1392** is a **T_HOLE**

FEATURE EVALUATION REPORT
C_Pocket Feature 38 has a Bottom-Fillet of Face 25 too small.
C_Pocket Feature 38 has a Draft-Angle of Face 11 OK
C_Pocket Feature 38 has a Top-Fillet of Face 9 too small

Protrusion Feature 513 has a Top-fillet of Face 464 too small
Protrusion Feature 513 has a Top-fillet of Face 328 too small
Protrusion Feature 513 has a Top-fillet of Face 116 too small
Protrusion Feature 513 has a Top-fillet of Face 83 too small
Protrusion Feature 513 has a Draft-Angle of Face 1579 OK
Protrusion Feature 513 has a Draft-Angle of Face 552 OK
Protrusion Feature 513 has a Draft-Angle of Face 576 OK
Protrusion Feature 513 has a Draft-Angle of Face 492 OK
Protrusion Feature 513 Bottom-Fillet: Fillet of Face 1579 does not exist
Protrusion Feature 513 Bottom-Fillet: Fillet of Face 552 does not exist
Protrusion Feature 513 Bottom-Fillet: Fillet of Face 576 does not exist
Protrusion Feature 513 has a Bottom-Fillet of Face 264 too small

Step Feature 264 has a Main-fillet too small
Step Feature 264 has a Draft-Angle of Face 492 too small
Step Feature 264 has a Draft-Angle of Face 16 OK.
Step Feature 264 has an external fillet of Face83 too small.
Step Feature 264 has an external fillet of Face153 too small.

Blind-Step Feature 3070 has a Main-fillet too small
Blind-Step Feature 3070 has a Draft-Angle of Face 2858 OK
Blind-Step Feature 3070 has a Draft-Angle of Face 2554 too small
Blind-Step Feature 3070 has a Lateral Draft-Angle of Face 3389 too small.
Blind-Step Feature 3070 has a Lateral Draft-Angle of Face 2283 too small.

Pocket Feature 3164 has a bottom-fillet of face 4466 too small.
Pocket Feature 3164 has a bottom-fillet of face 4182 too small.
Pocket Feature 3164 has a bottom-fillet of face 4175 too small.
Pocket Feature 3164 has a bottom-fillet of face 3523 too small.
Pocket Feature 3164 has a Draft-Angle of Face 2528 OK.
Pocket Feature 3164 has a Top-Fillet of Face 3363 too small
Pocket Feature 3164 has a Top-Fillet of Face 2766 too small
Pocket Feature 3164 has a Top-Fillet of Face 2244 too small
Pocket Feature 3164 has a Top-Fillet of Face 2711 too small

T_Hole Feature 174 can be moulded in the part
T_Hole Feature 174 has a Draft-Angle of Face 16 OK.

T_Hole Feature 817 requires special moulding process.
T_Hole Feature 817 can be moulded in the part
T_Hole Feature 817 has a cylinder angle that need to be aligned to Z axis

T_Hole Feature 969 requires special moulding process.
T_Hole Feature 969 can be moulded in the part
T_Hole Feature 969 has a cylinder angle that need to be aligned to Z axis

T_Hole Feature 1154 requires special moulding process.
T_Hole Feature 1154 can be moulded in the part
T_Hole Feature 1154 has a cylinder angle that need to be aligned to Z axis

T_Hole Feature 1392 requires special moulding process.
T_Hole Feature 1392 can be moulded in the part
T_Hole Feature 1392 has a cylinder angle that need to be aligned to Z axis
END OF FILE

Regarding the processing time for each stage of the recognition and evaluation process the results for sample part 2 are as follows:

Pre-processing including feature identification: 20 sec/all features.

Preparation of Identification Display files: 49 sec/all features

Evaluation including Display files: 25-sec/each features, average.

Figure 60 shows the SAT files created by FEBAMAPP as part of the feature evaluation process of sample part 2. These files are used to display the results of the analysis in the modeller used by the designer to create the model of the part. Identification of the features by FEBAMAPP was as expected and in full concordance with the feature identification performed by the expert, therefore once more FEBAMAPP achieved a 100% recognition of the features present in the model. The FEBAMAPP's recognition confidence factor ranges between 97% and 99% for this particular example as shown in Figure 59.

Regarding the identification task carried out by the expert, there were identified the following features: Through-Holes A, B, C, and D, Protrusion, Pocket, Circular-Pocket, Blind-Step and Step. Special attention was paid to the Through-Hole feature E, because according to the expert, this feature should be considered more as a Circular Pocket than a Through-Hole feature. Therefore, he suggested modifying this feature such that it would include a top-fillet according to the manufacturing process to be used. The total time used to identify the features was 50 seconds, which is about 2 ½ the time used by FEBAMAPP.

The results from the evaluation performed by the expert can be resumed as follows:

- Once more the fillets all around the part were considered to be inappropriate for the proposed manufacturing process, which according to the expert must be larger and should not have less than 6.0 to 8.0 mm.

- The draft angle was considered to be better for this sample part than for the first one, but still it was suggested that the draft angle of the Blind-Step should be increased from the actual 1.5 degrees to 3 degrees.

- There were not pointed out further potential problems related to the manufacture of this sample part.

The time required by the expert to perform the manufacturability analysis of this part was under 10 minutes, which still is more than twice the time used by FEBAMAPP.

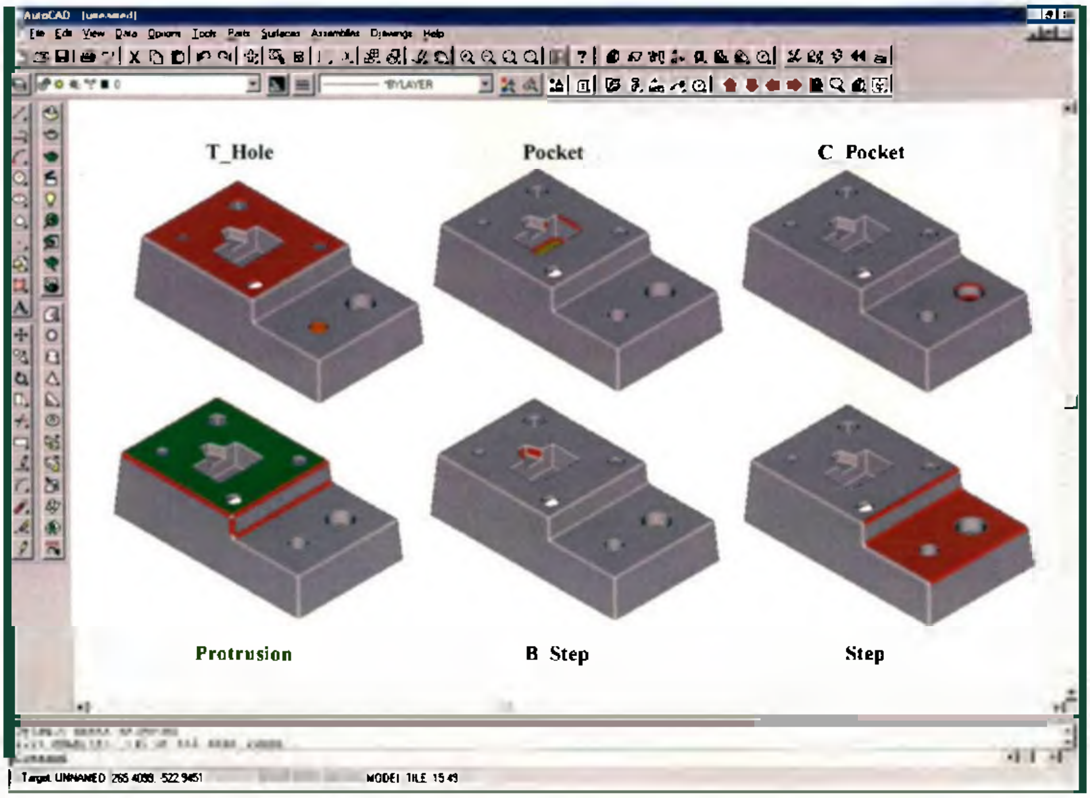
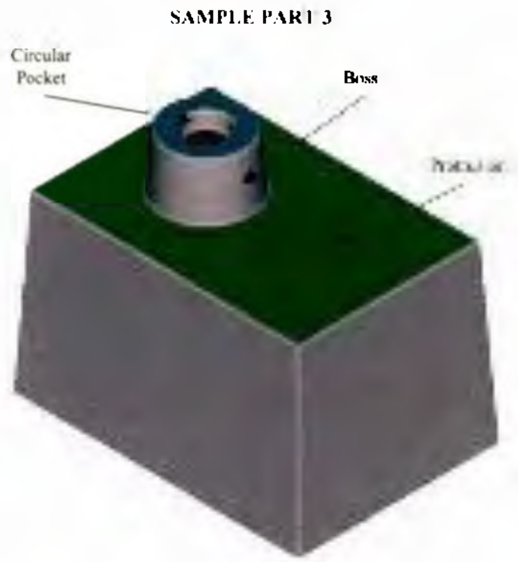


Figure 60. FEBAMAPP manufacturability evaluation results of sample part 2.

Evaluation results from FEBAMAPP were as expected with the exception of Through-Hole E, which was considered by FEBAMAPP as a "OK" feature in disagreement with the expert's opinion.

7.1.3 Sample part 3

Sample part 3 is a simpler sample with a reduced number of faces but still having three features. It is important to observe that this sample part contains a Circular-Pocket feature on top of the Boss feature. This combination of features could be interpreted as interfering features, but FEBAMAPP is able to identify both features individually. Figure 61 shows results of the feature recognition performed by FEBAMAPP.



FEATURE	Recognition confidence factor
Protrusion	[0.99034]
Circular Pocket	[0.99790]
Boss	]0.97980]

Figure 61. Feature identification results of sample part 3.

FEATURE IDENTIFICATION RESULTS

Potential Feature Matrix
Confidence Factors

Face	Pock	Step	Boss	Prot	Slot	Thnl	Cpck	Bstp
16	1.2e-11	6.1e-07	9.5e-19	7.1e-13	2.9e-07	8.2e-06	**0.99790**	4e-13
96	1.3e-11	6.9e-08	**0.97980**	1.5e-15	0.0042	7.1e-11	2.5e-05	4.9e-13
883	1.2e-11	5.3e-05	5.8e-05	**0.99034**	1.8e-05	8.4e-06	0.00073	4.1e-13

FEATURE IDENTIFICATION REPORT
Feature corresponding to **FACE 16** is a **C_POCKET**
Feature corresponding to **FACE 96** is a **BOSS**
Feature corresponding to **FACE 883** is a **PROTRUSION**

FEATURE EVALUATION REPORT
C_Pocket Feature 16 has a Bottom-Fillet of Face 9 too small.
C_Pocket Feature 16 has a Draft-Angle of Face 11 OK
C_Pocket Feature 16 has a Top-Fillet of Face 76 too small

Boss Feature 96 has a Top-Fillet of Face 195 too small.

Boss Feature 96 has a D/H ratio of Face 376 too small.
Boss Feature 96 has a Draft-Angle of Face 376 OK
Boss Feature 96 has a Bottom-Fillet of Face 831 too small

Protrusion Feature 883 has a Top-fillet of Face 1146 too small
Protrusion Feature 883 has a Top-fillet of Face 1051 too small
Protrusion Feature 883 has a Top-fillet of Face 612 too small
Protrusion Feature 883 has a Top-fillet of Face 545 too small
Protrusion Feature 883 has a Draft-Angle of Face 894 OK
Protrusion Feature 883 has a Draft-Angle of Face 1105 OK
Protrusion Feature 883 has a Draft-Angle of Face 223 OK
Protrusion Feature 883 has a Draft-Angle of Face 876 OK
Protrusion Feature 883 Bottom-Fillet: Fillet of Face 894 does not exist
Protrusion Feature 883 Bottom-Fillet: Fillet of Face 1105 does not exist
Protrusion Feature 883 Bottom-Fillet: Fillet of Face 223 does not exist
Protrusion Feature 883 Bottom-Fillet: Fillet of Face 876 does not exist
END OF FILE

Regarding the processing time for each stage of the recognition and evaluation process the results for sample part number 3 are as follows:

Pre-processing including feature identification: 7.5 sec/all features.

Preparation of Identification Display files: 4 sec/all features

Evaluation including Display files: 3-sec/each features, average.

Figure 62 shows the SAT files created by FEBAMAPP as part of the feature evaluation process of sample part 3. These files are used to display the results of the analysis in the modeller used by the designer to create the model of the part. Results of the feature recognition from FEBAMAPP were also as expected for sample part 3, and in full agreement with the expert's feature recognition results. The FEBAMAPP's confidence factor for recognition for this particular sample ranges between 97% and 99% as shown in Figure 61.

Regarding the identification task carried out by the expert, there were identified the following features: Protrusion, Circular-Pocket, and Boss. The total time used to identify the features was 10 seconds, which is slightly larger that the time used by FEBAMAPP.

The results from the evaluation performed by the expert can be resumed as follows:

- Once more the fillets all around the part were considered to be inappropriate for the proposed manufacturing process, but according to the expert, due to the simplicity of the part it should not represent a real threat for the moulding process.

- The draft angle of the cylinder corresponding to the Boss feature was considered to be too small for the ratio diameter/depth of the feature. Even worst, was the fact that the tool-gap between the Circular Pocket and the Boss was not large enough and, according to the expert, it would present manufacturing problems during the moulding process. Suggestion to fix this problem was as follows: reduce the depth of the Boss feature for as much as the design constraints will allow it or increase the diameter of the Boss feature.

- There were not pointed out further potential problems related to the manufacture of this sample part.

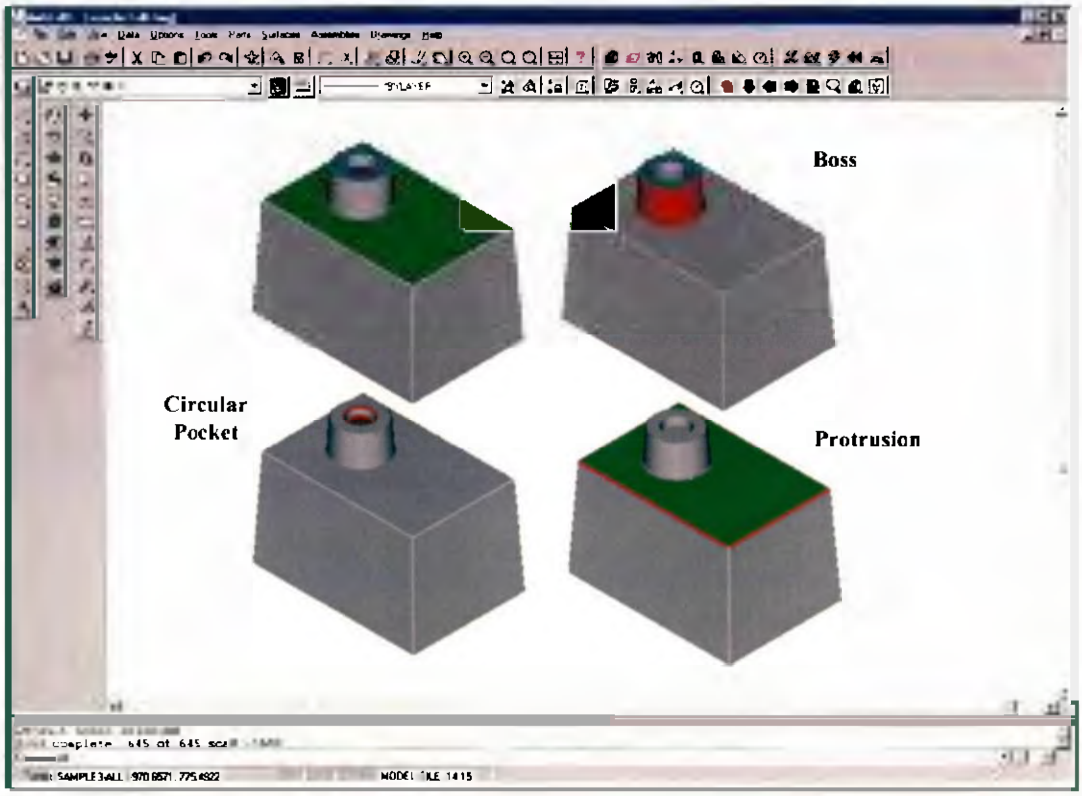


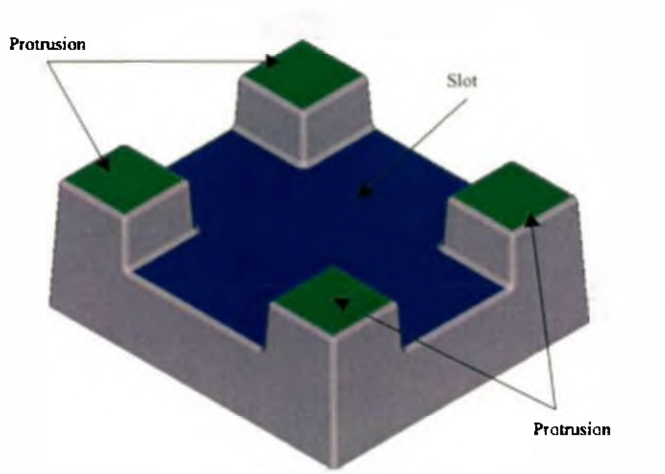
Figure 62. FEBAMAPP manufacturability evaluation results of sample part 3.

Regarding the results of the evaluation made by FEBAMAPP, the potential threat from the reduced tool-gap between the Boss and the Circular-Pocket was not considered by FEBAMAPP as it was by the expert.

7.1.4 Sample part 4

Sample part 4 represents a model of a part with 176 faces including a complex feature, which is one of those features known in machined applications of feature recognition as interfering features. This particular feature named Cross-Slot was not included in the training of the feature recognition system, but still FEBAMAPP was able to recognise the Cross-Slot feature as a simple Slot feature, as shown in Figure 63. This fact demonstrates the capabilities of the system on generalising, and mapping unknown FVectors to the closest feature already stored in the system database.

SAMPLE PART 4



FEATURE	Recognition confidence factor
Protrusion	[1.000]
Protrusion	[1.000]
Protrusion	[1.000]
Protrusion	[1.000]
Slot	[0.9987]

Figure 63. Feature identification results of sample part 4.

Regarding the evaluation of the features present in sample part four, there was no problem evaluating the protrusion features. The evaluation of the recognised Slot is a little more complicated because it presents a divergence between the parameters to be evaluated in the original Slot feature and the parameters that need to be evaluated in the actual Cross-Slot feature. The major concern is related to the fact that FEBAMAPP will not be able to evaluate all faces belonging to the Cross-Slot feature. Nevertheless, FEBAMAPP was able to perform a partial evaluation of the feature and detect some manufacturing problems related to the fillet radii in some surfaces of the model. Results of the Slot evaluation are displayed using AutoCAD as shown in Figure 64.

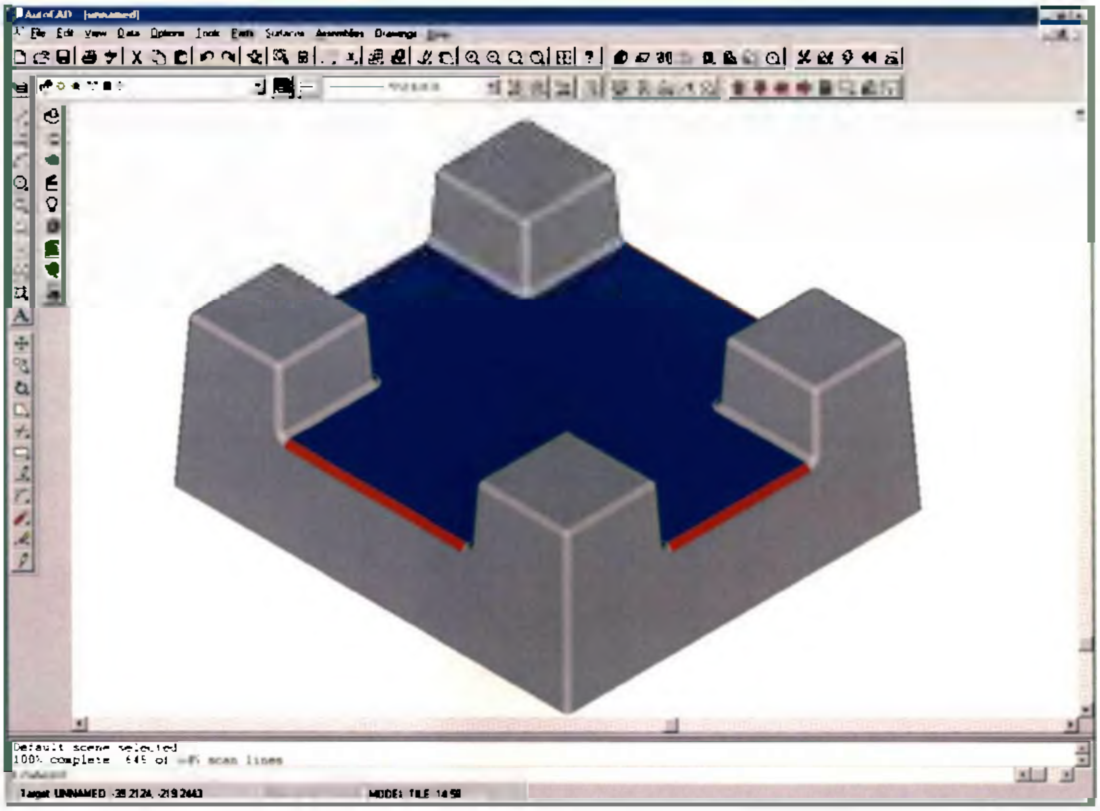


Figure 64. Results of the Cross-Slot feature evaluation.

FEATURE IDENTIFICATION RESULTS

Potential Feature Matrix
Confidence Factors

Face	Pock	Step	Boss	Prot	Slot	Thol	Cpck	Bstp
1099	1.2e-11	2.7e-05	5.9e-05		2.2e-07	5.3e-07	6.3e-06	3.9e-13
2198	1.2e-11	2.7e-05	5.9e-05		2.2e-07	5.3e-07	6.3e-06	3.9e-13
1959	1.2e-11	2.7e-05	5.9e-05		2.2e-07	5.3e-07	6.3e-06	3.9e-13
5072	1.2e-11	2.7e-05	5.9e-05		2.2e-07	5.3e-07	6.3e-06	3.9e-13
2390	1.2e-11	7.6e-08	0.091	7e-14	**0.9987**	2.3e-05	0.79	4.1e-13

FEATURE IDENTIFICATION REPORT

Feature corresponding to **FACE 1099** is a **PROTRUSION**
Feature corresponding to **FACE 2198** is a **PROTRUSION**
Feature corresponding to **FACE 1959** is a **PROTRUSION**
Feature corresponding to **FACE 5072** is a **PROTRUSION**
Feature corresponding to **FACE 2390** is a **SLOT**

FEATURE EVALUATION REPORT

Protrusion Feature 1099 has a Top-fillet of Face 1050 too small
Protrusion Feature 1099 has a Top-fillet of Face 802 too small
Protrusion Feature 1099 has a Top-fillet of Face 379 too small
Protrusion Feature 1099 has a Top-fillet of Face 280 too small
Protrusion Feature 1099 has a Draft-Angle of Face 2544 OK
Protrusion Feature 1099 has a Draft-Angle of Face 1746 OK
Protrusion Feature 1099 has a Draft-Angle of Face 1358 OK
Protrusion Feature 1099 has a Draft-Angle of Face 1079 OK
Protrusion Feature 1099 Bottom-Fillet: Fillet of Face 2544 does not exist
Protrusion Feature 1099 has a Bottom-Fillet of Face 2961 too small
Protrusion Feature 1099 Bottom-Fillet: Fillet of Face 1358 does not exist
Protrusion Feature 1099 has a Bottom-Fillet of Face 2193 too small

Protrusion Feature 2198 has a Top-fillet of Face 3942 too small
Protrusion Feature 2198 has a Top-fillet of Face 3303 too small
Protrusion Feature 2198 has a Top-fillet of Face 2468 too small
Protrusion Feature 2198 has a Top-fillet of Face 1971 too small
Protrusion Feature 2198 has a Draft-Angle of Face 4218 OK
Protrusion Feature 2198 has a Draft-Angle of Face 1680 OK
Protrusion Feature 2198 has a Draft-Angle of Face 2152 OK
Protrusion Feature 2198 has a Draft-Angle of Face 1358 OK
Protrusion Feature 2198 has a Bottom-Fillet of Face 4527 too small
Protrusion Feature 2198 Bottom-Fillet: Fillet of Face 1680 does not exist
Protrusion Feature 2198 has a Bottom-Fillet of Face 1022 too small
Protrusion Feature 2198 Bottom-Fillet: Fillet of Face 1358 does not exist

Protrusion Feature 1959 has a Top-fillet of Face 3744 too small
Protrusion Feature 1959 has a Top-fillet of Face 3649 too small
Protrusion Feature 1959 has a Top-fillet of Face 3379 too small
Protrusion Feature 1959 has a Top-fillet of Face 3284 too small
Protrusion Feature 1959 has a Draft-Angle of Face 1264 OK
Protrusion Feature 1959 has a Draft-Angle of Face 2336 OK
Protrusion Feature 1959 has a Draft-Angle of Face 2442 OK
Protrusion Feature 1959 has a Draft-Angle of Face 1680 OK
Protrusion Feature 1959 Bottom-Fillet: Fillet of Face 1264 does not exist
Protrusion Feature 1959 has a Bottom-Fillet of Face 549 too small
Protrusion Feature 1959 has a Bottom-Fillet of Face 1940 too small
Protrusion Feature 1959 Bottom-Fillet: Fillet of Face 1680 does not exist

Protrusion Feature 5072 has a Top-fillet of Face 4762 too small
Protrusion Feature 5072 has a Top-fillet of Face 4447 too small
Protrusion Feature 5072 has a Top-fillet of Face 3462 too small
Protrusion Feature 5072 has a Top-fillet of Face 2865 too small
Protrusion Feature 5072 has a Draft-Angle of Face 4951 OK
Protrusion Feature 5072 has a Draft-Angle of Face 1264 OK
Protrusion Feature 5072 has a Draft-Angle of Face 2544 OK
Protrusion Feature 5072 has a Draft-Angle of Face 5138 OK
Protrusion Feature 5072 has a Bottom-Fillet of Face 1876 too small
Protrusion Feature 5072 Bottom-Fillet: Fillet of Face 1264 does not exist
Protrusion Feature 5072 Bottom-Fillet: Fillet of Face 2544 does not exist
Protrusion Feature 5072 has a Bottom-Fillet of Face 4546 too small

Slot Feature 2390 has a bottom-fillet of face 4209 too small.
Slot Feature 2390 has a bottom-fillet of face 3729 too small.
Slot Feature 2390 has a bottom-fillet of face 2414 too small.
Slot Feature 2390 has a bottom-fillet of face 472 too small.
Slot Feature 2390 has a Draft-Angle of Face 1680 OK.
Slot Feature 2390 has a Draft-Angle of Face 2544 OK.

Slot Feature 2390 has a Draft-Angle of Face 1264 OK.
Slot Feature 2390 has a Draft-Angle of Face 1358 OK.
Slot Feature 2390 Top-Fillet: Fillet of Face 1680 does not exist
Slot Feature 2390 Top-Fillet: Fillet of Face 2544 does not exist
Slot Feature 2390 has a Top-Fillet of Face 4447 too small.
Slot Feature 2390 has a Top-Fillet of Face 1971 too small.

This sample part was not presented to the expert for evaluation. The processing time for each stage of the recognition and evaluation process carried out by FEBAMAPP on sample part 4 is as follows:

Pre-processing including feature identification: 34 sec/all features.

Preparation of Identification Display files: 26 sec/all features.

Evaluation including Display files: 48-sec/each features, average.

Recognition of the features in sample part 4 was better than expected, because the program was able to recognise a potential Slot feature from the Cross-Slot present in the part. The Cross-Slot was never before presented to the system for recognition.

7.2 DISCUSSION OF RESULTS

The discussion of results will be concentrated on the main research issues considered in this thesis, as they were stated in the aim and goals of the research in Chapter 1. Therefore, analysis will be made about the correctness of the object representation used in the research and the methodology followed to transform the solid model into a convenient input pattern for a neural network system.

Also, consideration would be made regarding the application of a three-layer feed-forward neural network system to the recognition of 3-Dimensional features in solid models of reinforced plastics components.

Further analysis will be focused on the methodology used to perform a rule-based manufacturability analysis of the features considered in this research. Comparison of the results obtained from the application of the FEBAMAPP manufacturability system with the evaluation results obtained from an expert will also be carried out.

Finally, consideration of the FEBAMAPP's hardware requirements is made in this chapter.

7.2.1 Object Representation

The first step in the manufacturability analysis performed by FEBAMAPP is the Pre-Processing of the solid model text file, also known as the SAT file. Pre-Processing the SAT file means transferring all relevant information stored in the solid modeller database into the feature recognition and evaluation application. It can be considered as one of the most important stages in the feature recognition and evaluation tasks performed by FEBAMAPP. It is at this stage where FEBAMAPP generates a set of FVectors (one for each face in the model), by considering the geometrical and topological information regarding faces, edges and vertices of the modelled part. This research considers only manifold objects, where space is unambiguously divided into solid and void space by the boundaries or faces of the manifold solid. It is also considered that exactly two faces meet in an edge, but more than three faces can share a vertex.

Most feature recognisers available in the market assume that the model has only sharp edges, such as the recognisers from Chuang and Henderson, 1990;

Chamberlain, et al, 1993; De Martino, et al, 1994; and Gadh and Prinz, 1995; which is not a real situation. In reality, even for machined features the cutting edges cannot be perfectly sharp due to the natural radii of the cutting tools or due to design specifications intended to reduce stress concentrations on the model. FEBAMAPP considers the presence of fillets along the edges of the model, unless it is a boundary edge of the part.

Some recent works (Kumar, et al, 1996; Sonthi and Gadh, 1998; Zhao, et al, 1999) attempt to recognise features including fillets. The approaches followed in these researches are based on changing the filleted model into a sharp edge model and then performing the feature recognition in the modified model. FEBAMAPP attempts to perform feature recognition of filleted features without modifying the original model by using a Neural Network system. Advantages of this approach include the speed of recognition and the ability of the system to perform recognition under the presence of incomplete data or interfering features.

The results of this research show that the nine-element FVectors used as input to the NN system have enough information to represent unequivocally each one of the 3-Dimensional features under consideration in this research. An FVector is constructed using the "Face Score" of the face under evaluation plus the "Face Score" of up to a maximum of eight (8) "Surrounding Faces".

7.2.2 Feature Recognition

The feature recognition task is seen as matching a certain FVector to a pre-determined pattern vector stored in the system database. The order used to present data to the Neural Network system is important because a Neural Network reads numbers in sequence. Therefore, a further classification of surrounding faces into "Sharing-Vertex" and "Sharing-Edge" faces is used to assign the position of the corresponding "Face Score" in the FVectors, giving in this way the necessary 'shape' to the FVector required by the Neural Network while performing the pattern recognition task.

"Face Scores" are based on the concavity and convexity of the surface, the edges and the vertices belonging to the face under evaluation. A convention was used to assign positive values (+2) to convex surfaces and negative values (-2) to concave surfaces.

Special cases are used for plane and spline surfaces because these surfaces can be considered neither convex nor concave, therefore its value is assumed to be zero (0). Concavity or convexity of a face is determined based upon the curvature of the surface and the direction of its Normal vector. The features differentiation approach used in this research seems to be appropriated and it was possible to clearly separate concave from convex regions in the modelled parts. In some cases where one feature can be seen as geometrically opposite to each other, then their corresponding FVectors are symmetric in reference to the X axis, as it is shown in Figure 65 for Boss and Circular Pocket features.

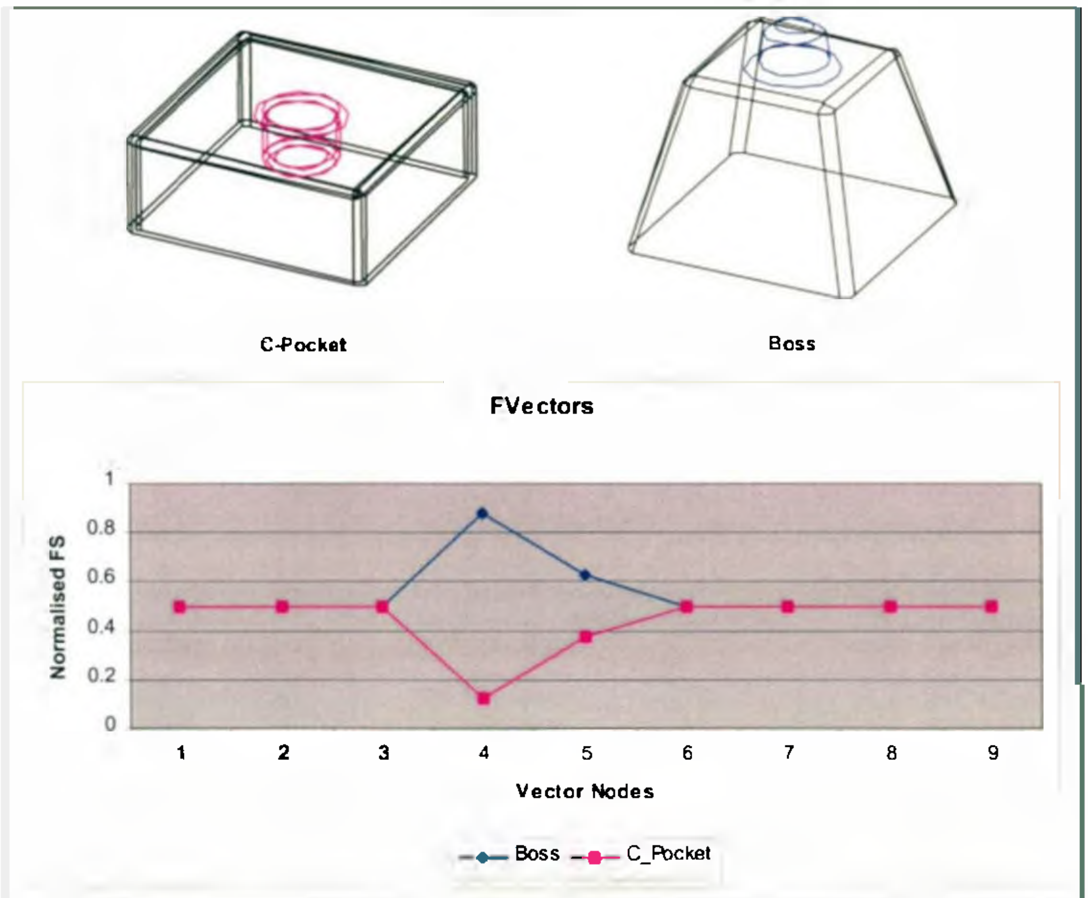


Figure 65. Symmetric features and their corresponding symmetric FVectors.

The surface types used in the construction of the solid models used as samples in this research are Cone, Sphere, Torus, Plane and Spline; which in different combinations can represent complex objects.

A three-layer perceptron neural net was used to solve the feature recognition problem. A three-layer perceptron is able to create any convex solution region in the given space determined by the input patterns. The convex regions are created by the intersection between the regions created by each neurone in the hidden-layer, where each of those neurones behaves as a single perceptron. The solution-region given by such intersection will be a convex region with a number of sides equal to the number of neurones in the hidden-layer.

The previous statement set the boundaries necessary for the selection of the number of neurones in the hidden-layer. The number of neurones in this layer will be as large as required to create a solution region complex enough to solve the problem, but not too large that the weight estimation for the number of available input patterns becomes unreliable. Several neural net configurations were tested during FEBAMAPP construction to find out an acceptable net architecture in terms of training time and recognition performance. The final net architecture used in this research is a three-layer perceptron system with nine (9) neurones or nodes in the input-layer, four (4) neurones in the hidden-layer, one (1) neurone in the output-layer and a total of eight (8) neural networks; one for each feature to be recognised.

Regarding the training of the nets, a back-propagation algorithm was used, which is a training algorithm that can be applied to networks with more than two layers of neurones. Probably, the most important characteristic of this algorithm is its capability for organising the internal representation of the knowledge in the hidden-layer, such that it is able to find any correspondence between the input-layer and the output-layer of the net.

The back-propagation algorithm finds a minimum value of the error function (local or global) by means of the Decreasing Gradient technique. Therefore, one of the problems of this algorithm is that it can fall into a local minimum of the error function, not being able to find the global minimum. Nevertheless, it is not absolutely necessary to find the global minimum in all applications, and a local minimum can be good enough to solve the problem.

Since using small increments in the weights is recommended when looking for the minimum of the error function, then a small value of the learning parameter α (0.20) was selected. The learning parameter has a major influence in the convergence speed of the algorithm, the smaller the parameter the greater the number of iteration required, but using a large value can bring the fact that a minimum is never reached. In practice if a net stop learning, before reaching an acceptable value for the error, then there are a few approaches that can be used to solve the problem. Firstly, it may be necessary to change the number of neurones in the hidden-layer. Secondly, a change in the learning parameter can help to reach a suitable minimum. Thirdly, starting a new training session using a different set for the weights in the network connections can also solve the problem. At some point all of these tools were used in the training of the neural network system developed as part of this research.

The total number of iterations required for training of each one of the nets used in the FEBAMAPP system ranged between 4000 cycles for Protrusion features and 6000 cycles for Blind-Step features. A computer with a Pentium II CPU and 266 MHz Processor was used and a real training time between 3.5 and 7 minutes were required for the networks to converge to an acceptable minimum of the error function. Training of the networks is a one-off task, therefore it can be considered as an acceptable time for training of the networks. Once the network parameters were established during the training, they were included in the main source program of FEBAMAPP.

Future expansion of the system for recognition of more features under the same reinforced plastics application or recognition of features related to a different application, will require training of a new set of neural networks and update of the system in terms of feature recognition training parameters.

Several modelled objects were used to test the ability of FEBAMAPP to perform feature recognition, where very promising results were obtained. The system shows an excellent performance regarding the time required for recognition based on the fact that only arithmetic computations are required. Therefore, there is no need for a complex search of graphs in the object database as it is necessary in other feature recognisers such as: Chuang and Henderson, 1990; Gadh and Prinz, 1995; Vandenbrande and Requicha, 1993.

Both memory storage and computational upper bound complexities, according to the Knuth notation (Knuth, 1976), are in the order of O(F) algorithms, where F is the number of faces in the modelled object. Pre-processing of the SAT and feature recognition requires processing once each face of the object to complete the feature recognition task. Even though the Pre-processing task requires reading the SAT file and this is not a sequential task, it still is of a lineal complexity with a constant depending on the number of faces and edges of the object.

FEBAMAPP is not intended for recognition of partial features but potential features according to the patterns used during the training of the system. Therefore, all those faces with confidence factors below 0.9 (90%) are not considered as representatives of any particular feature. Future research may be carried out regarding the recognition and/or evaluation of partial features, but it is out of the scope of the present work. Nevertheless, FEBAMAPP is able to recognise some intersecting features as the Cross-Slot presented in the sample part 4.

The three-layer perceptron can only recognise "potential" features by using the confidence factor given by the Neural Network system, therefore to achieve the final feature recognition, a certain number of conditions need to be added to the system. Added conditions to the feature recognition system include rules regarding:

- Direction of normal vectors of the surfaces or faces.
- Angle between the surrounding faces and the face under evaluation.
- Angle between the surrounding faces and the drawing direction (Z+) of the part.
- Convexity or concavity of surrounding faces, and
- Angle of the main axis of cones and torus surfaces.

Lets use the Protrusion feature shown in Figure 66 as an example to highlight this point. Since, most of the objects manufactured by reinforced plastics are hollow objects, then a Protrusion feature can be seen from the back of the objects as a Pocket feature. But, if a condition regarding the direction of the Normal vector of the feature's main face is added, then it is possible to discriminate between the options and to identify the correct feature. In both cases, Protrusion and Pocket features, the angle between the Normal vector to the feature's main face and the Z+ axis must be less than 90°. In this way the back of a Protrusion feature would not be considered as a recognised Pocket feature. The same example applies when the Pocket feature is being recognised and the back of it cannot be mistaken as a Protrusion feature.

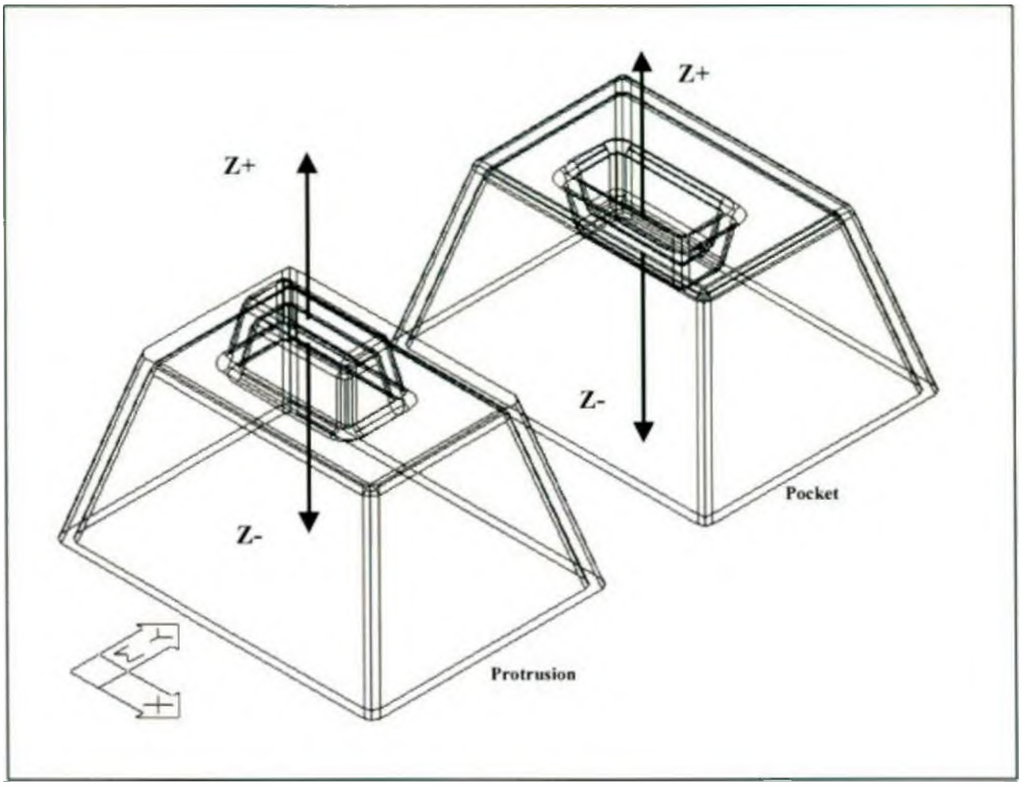
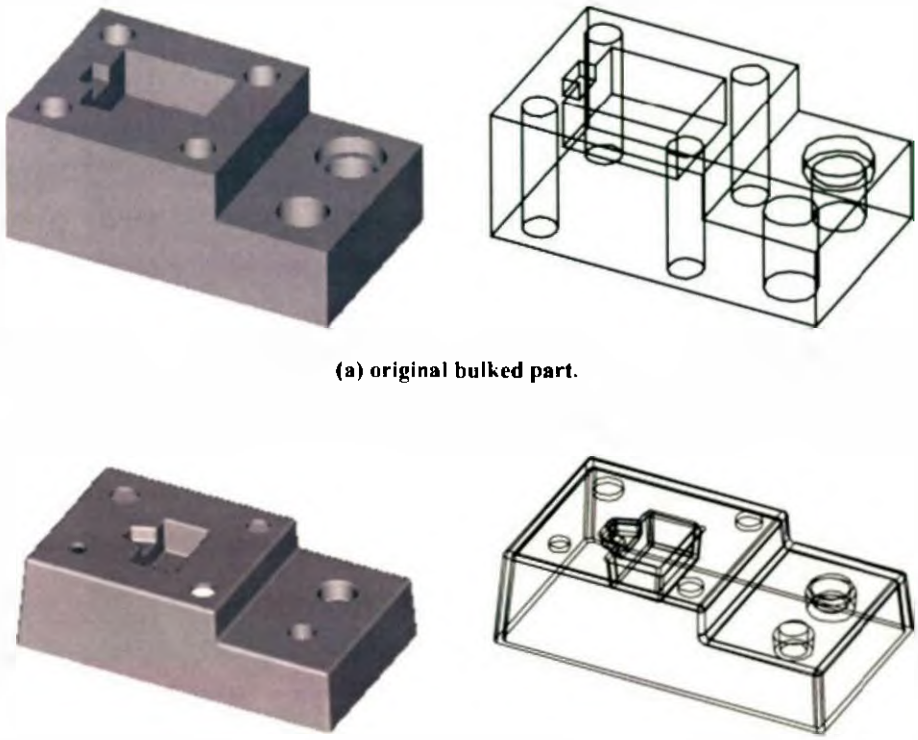


Figure 66. Use of the Normal vector as a medium to discriminate between potential features.

Due to the lack of other applications using hollow models during feature recognition, then an object used for demonstration in several references (Sakurai and Gossard, 1988; Hummel, 1989; Chuang, 1991; Hwang, 1992) was adapted to the reinforced plastic application. This adaptation was used to compare in some way FEBAMAPP performance of feature recognition with those results achieved by other researchers in the field. The changes required by the sample part are mainly that instead of a solid bulk part it was transformed into a thin-walled (hollow) object. Also, fillets were added along all internal edges and a draft angle was given to vertical walls. Figure 67(a) shows the original part and 67(b) the modified sample part.



(a) original bulked part.

(b) Transformed hollowed part.

Figure 67. Selecting a suitable model for comparing FEBAMAPP performance.

Introducing such modifications in the original part brings some dramatic changes in the model's characteristics, but still it is useful when comparing FEBAMAPP expected results with some actual results given by other applications.

In the first place, the number of faces in the model changes from 26 faces in the original model to 170 faces in the actual model. The difference in the number of faces corresponds to the number of faces added to the model to transform it into a hollowed part plus the number of faces added as fillets between faces and around corners in the vertices of the part. For instance, it is possible to see that the Blind-Step feature has 4 faces in the original bulk model and for the hollow part its number of faces is increased to 23. This is only for the front side of the object, but since it is a hollow part then there are 23 more faces added in the back of the object that also require processing and evaluation. A wire-frame detail of a Blind-Step feature is shown in Figure 68. where it is possible to observe the faces involve in this feature.

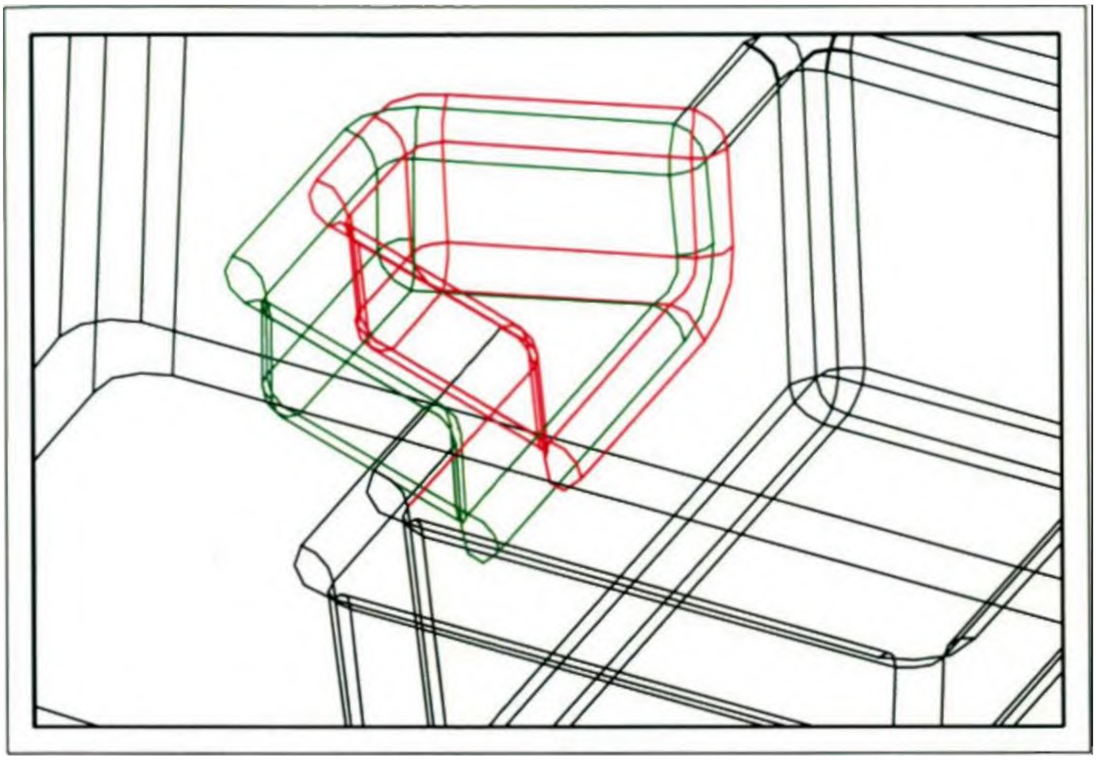


Figure 68. Wire-frame detail of a Blind-Step feature.

Red colour for front side and green for back side

Regarding the processing time, Chuang (Chuang, S., 1991) reported that using graph matching took over 150 seconds (2 ½ minutes) to complete the feature recognition in the original sample part. Hwang (Hwang, J.L., 1992) reported a total time of 0.61 seconds using a perceptron. Unfortunately, the processor used was not mentioned in these reports, therefore it is not possible to compare FEBAMAPP performance under the same platform. FEBAMAPP requires 15.8 seconds to complete the feature recognition including pre-processing of the SAT file and generation of the output file with the recognition results.

At an extra cost in terms of processing time, FEBAMAPP is able to prepare a visual display of the results from the feature recognition task. This visual display is formed by a series of SAT files, which use a colour code to represent the recognised features. These SAT files can be used in conjunction with the text output file and displayed in the application currently in use for modelling the part, such as

AutoCAD, CADKEY, CATIA, IDEAS or other solid modellers as long as they are able to create and display an SAT file.

FEBAMAPP will create individual SAT files for each type of feature the user selects to be recognised plus an SAT file, which includes all types of recognised features in the modelled part. Another option available in the system, as part of the feedback facilities of FEBAMAPP, is the creation of an SAT file for display of a particular feature as required by the user. This last option requires identification from the user of the identifying tag of the face from the text output file, and uses it as input in the corresponding text box of the Display Features window of the application. FEBAMAPP will create an SAT file with the name 'Face.sat' to store this information. Details regarding use of this option can be found in the available Help facility of the system. Creation of the 'All-Feature.sat' file for visual feedback and display of the feature recognition results from FEBAMAPP takes 49 seconds including the 10 features present in the model.

Individual SAT files for the different feature types take a time ranging from 4.9 seconds for features with only one occurrence in the model such as Circular-Pocket and Protrusion, to 24.5 seconds for Through-Hole features with five occurrences in the file. It can be observed from the previous results that the time required for preparing the SAT file for visual feedback depend on the number of features present in the model and also in the number of total faces in the model. Less complex objects will have faster processing times.

Finally, it must be said that the results obtained from FEBAMAPP, in the feature recognition task, are as expected and that 100% of the trained features presented in the model were recognised with a confidence factor of 90% or higher.

7.2.3 Feature Evaluation

Regarding feature evaluation, FEBAMAPP bases its analysis in what it can be considered as an extension of the Feature concept. For instance, if the manufacturability analysis of a particular modelled object is based on the fact that a 'manufacturing feature' is any region of the object with some manufacturing importance, then evaluating the characteristics of such a region is equivalent to the evaluation of the feature itself.

Basically, FEBAMAPP compares the geometric information of the features with information stored in the system database. There are 'target' or minimum values that must be matched by some of the feature parameters, where the target values will depend upon the manufacturing process and materials selected as part of the model's evaluation.

Internal and external characteristics of the features are used to perform the manufacturability evaluation of the modelled part. Internal characteristics correspond to the geometry of the feature in terms of dimensions, dimensions ratios, angles, radii of fillets and draft angles. Based on the fact that sometimes it is not possible to give a constant value to a particular feature characteristic, then some geometric characteristics are represented as a 'ratio' between two dimensions of the feature. This is particularly useful when dealing with non-dimensional objects where the scale used during its creation becomes irrelevant. External characteristics of a feature are those related to the interaction between the evaluated feature and other features in the model. Usually, external features are evaluated in terms of tool-gap, distance between the feature and the external edges of the part and distance between adjacent features. Upper limit to these variable values is based on the intended manufacturing process and the selected materials for the modelled part.

Results from the feature evaluation are also stored in the text file 'Feature.out', along with the results from the feature recognition task. Each feature has particular characteristics to be checked. The evaluation procedure starts by getting all geometrical information regarding the feature or features to be analysed in terms of its internal characteristics. Typical information includes main face's dimensions, radii of fillets along the edges of the main face (also called 'bottom fillet'), radii of fillets between lateral walls of the feature or cone angle accordingly to the feature case and its surface type, draft angle of lateral walls, and radii of fillets in the outer limit of the feature (also called top-fillet).

In relation to the external characteristics of the feature, information regarding the main face vertices' co-ordinates, vertices' co-ordinates of the most external faces of the feature and type of edges surrounding those faces is required. Also, there are required the vertices' co-ordinates and edge types of the adjacent faces to the most external faces of the feature. These values will be used to evaluate the tool-gap and possible interference between adjacent features during the manufacturing of the part. Furthermore, the position of the feature in relation to the edges of the part is checked to avoid weakness of the part due to features located too close to the external edges of the part.

Results from the feature evaluation are reported using the face tag to identify the face being evaluated and the results in terms of the variables involved in its evaluation. Only variables failing to meet the target values are reported in the results.

Once more, target values for the variables will depend upon the manufacturing process being considered and the materials to be used for manufacturing the part. Therefore, some variables could have satisfactory results for one particular manufacturing process and fail the evaluation for others.

During the feature evaluation there is the option for the user to select the feature or features to be evaluated, along with the manufacturing process and kind of materials to be used. Since there is no chance for FEBAMAPP to know the intended purpose of the design it is not an easy task to advise the user about the best combination of resin and reinforcement for a particular application. Nevertheless, there is enough information in the help facility of the system to assist the user in the materials and process selection based in the information regarding the intended use of the part, conditions of work, intended production rates, surface finish and size of the part.

Materials selection is a task that should be performed prior to the evaluation of the part, but FEBAMAPP uses default values for such variables if the user does not select a particular combination materials-process. The default materials used for evaluation are E-Glass as the reinforcement and Polyester thermosetting resin, which are the most popular combination of materials that can be used in a broad range of applications and manufacturing processes. FEBAMAPP uses Hand Lay-up process as default manufacturing process.

The final decision about changes in the design is left to the designer. FEBAMAPP will only give suggestions about which faces in each feature are representing a potential manufacturing threat, and also some explanations of the possible problems expected if no-change is made in the design.

The fact that FEBAMAPP requires one neural network for each feature to be recognised increases the training time of the system, but it really can be seen as an advantage. Firstly, it allows the system to be easily updated adding new features to it if necessary. Secondly, change in one of the present features can be done without the need to change all features' information in the system. Another advantage is that using a recognition-menu specific feature can be searched on the model according to the user specification.

The scope of the proposed system is to provide designers with early support in terms of manufacturing capabilities and limitations of available manufacturing processes so that design of reinforced plastic components can be improved from the initial design stages. It allows a particular design to be tested against different reinforced plastic manufacturing processes and identify potential problems related to manufacture in later stages of the product development process.

Regarding the evaluation of the features carried out by FEBAMAPP; there were some disagreements with the expert opinion regarding the values of some of the variables and their influence in the difficulties expected during manufacture of the parts. An example of this situation is the case of the Circular-Pocket feature, which was in top of the Boss feature in sample part 3, where according to the expert there was not an appropriate tool-gap as consequence of the interaction between these two features and FEBAMAPP did not pointed out this possible design error.

7.2.4 Hardware Requirements

Borland C++ was used as the main programming tool to develop FEBAMAPP as a Windows application running on a low performance personal computer. Therefore, the goal of developing the application in such a way that it were of easy reach by the SMMEs companies dedicated to the manufacture of reinforced plastics components, was successfully accomplished.

Chapter 8

8 CONCLUSIONS AND FURTHER WORK

8.1 Conclusions

A high performance feature-based manufacturability analysis of plastic parts (FEBAMAPP) system is presented which consists of:

- Automatic identification of the features present in the model
- Evaluation of internal and external characteristics of the features previously identified in the model, and
- A design-recommendation database used to advise the users about potential manufacturing threats that could be presented in the modelled part.

The face vector (FVector) concept used in this research seems to be appropriated to represent the solid's geometrical and topological characteristics of the model leading toward a straightforward three-dimensional (3D) feature recognition algorithm using a neural network (NN) methodology approach.

The confidence factor given by the Neural Network system is not enough to perform a definitive recognition of the features. Therefore, it is necessary to use complementary rules regarding geometrical characteristics of the surrounding faces of the feature's main face to complete the feature recognition process. Complementary rules include information regarding the normal vectors of the surfaces surrounding the face under evaluation, the angle between faces, and the type of fillet used to blend the evaluated face and its adjacent faces.

The system has proved its capability to handle recognition of features under the presence of fillets, where a 100% of the trained features were recognised with a recognition confidence factor of 90% or higher, as it was shown in the samples presented in Chapter 6. Fillets are one of the main characteristics of the design of plastic parts, which is not considered in feature recognisers as used in traditional metal-machined component. Actual feature recognisers used in the plastic industry modify the actual model in such a way that fillets are removed so it is possible to use traditional feature recognisers as used in the evaluation of machined components. FEBAMAPP is the first attempt to use NN in the recognition of 3D features in a filleted model.

Based on the recognition rate and precision observed during the testing phase of the system, it is possible to confirm that the hybrid Text File-Neural Network system shows high performance on the recognition of manufacturing features on this particular application. The fact that FEBAMAPP uses a text file as input of the system, and that the format of this text file is widely used in the solid modellers available in the market such as AutoCAD, CATIA, CADKEY, ProEngineer, and others; makes FEBAMAPP a potential tool for the analysis of manufacturability of reinforced plastics components.

The manufacturability analysis approach used in this research focuses on features in the model and attempts to guide the designer in such a manner that internal and external characteristics of those features can be improved reducing global manufacturing difficulties during later stages in the product development process.

Since the system is not able to handle information regarding the intended design, then design recommendations are intended to specifically improve each feature instead of attempting to be global design recommendations for the whole component. Final changes to the original model are left to the criteria of the designer. FEBAMAPP is not able to modify the original model of the part.

The system shows a particularly inexpensive computational algorithm, which is suitable to run in low range computers making it accessible to SMMEs. The implementation of this system, in the SMMEs in the field of reinforced plastic manufacturing, could reduce the lead-time and enhance the final design reliability of reinforced plastic components.

8.2 Original Contribution

The goal of this research is to link the gap between design and manufacture of reinforced plastic components by using a feature-based manufacturability evaluation of a B-Rep model of the intended part. In developing the present system the following tasks can be considered to be original contributions of this research:

- The conceptual evaluation of a solid-model used to transform topological and geometrical characteristics of a 3-D solid B-Rep of a filleted model into a set of floating points (FVectors) such that this information can be used as a neural network input for feature recognition. Such a transformation is based on the convexity and concavity of the model faces, edges and vertex.

- A new attempt was made to apply the three-layer perceptron to 3D-feature recognition. This time features were specific related to the reinforced plastic manufacturing process, where handling hollow parts and the presence of fillets are of capital importance.

- The integration of the design and manufacturing information as a set of production rules with a neural network based feature recognition into a robust rule-based manufacturability analysis system to assist design of reinforced plastic components in the early stages of the product development process.

8.3 System Limitations

Even though an effort has been made to include the most important features to be considered during the design for manufacture of reinforced plastics components, the number of features considered may not be enough to perform a thorough evaluation of all reinforced plastics components.

The manufacturability evaluation carried out for FEBAMAPP considers the part to be produced and not the mould to be used, therefore some difficulties may arise during the construction of the mould, which must be further evaluated using a manufacturability analysis for machined components or other appropriate tools.

Evaluation of recognised features not included during the training of the system will not include the appropriate parameters of evaluation; therefore it is highly recommended that the designer verify the results of the evaluation of such features.

An important limitation of the system is the fact that the visual feedback of the evaluation results cannot be displayed inside FEBAMAPP, which may represent a delay in the evaluation process and discomfort for the users.

8.4 Further Work

It is apparent, from the results of this research and considering the design capabilities of the processes involved, that to improve the linking between design and manufacture of reinforced plastic components further investigation in feature recognition and evaluation is required. Further work should include an extension of the set of features to include complex and/or partial features including free form sculptured surfaces and interacting features. Also, research should be carried out regarding the recognition of features on filleted model including non-uniform radii fillets and/or mixed radii fillets.

Since the manufacturing of reinforced plastic components has many common characteristics with other manufacturing processes such as plastic injection and foundry, it could be possible to extend the present work by training specific networks to perform feature recognition and consider manufacturability analysis of such processes.

Finally, an effort should be carried out to integrate the visual display of results as part of the main application, such that FEBAMAPP can be used as a completely independent manufacturability analysis tool.

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APPENDICES

Appendix 1. Neural Network definition files.

Definition of Neural Networks used for feature recognition in FEBAMAPP system.

```
SNNS network definition file V1.4-3D
generated at Thu Feb 24 12:55:00 2000

network name : Boss4
source files :
no. of units : 14
no. of connections : 40
no. of unit types : 0
no. of site types : 0

learning function : Std_Backpropagation
update function   : Topological_Order

unit default section :
act      | bias     | st | subnet | layer | act func     | out func
---------|----------|----|--------|-------|--------------|----------
 0.00000 |  0.00000 | h  |      0 |     1 | Act_Logistic |
Out_Identity
---------|----------|----|--------|-------|--------------|----------

unit definition section :
no. | typeName | unitName | act      | bias     | st | position  | --
----|----------|----------|----------|----------|----|-----------|---
  1 |          |          |  0.50000 | -0.02774 | i  |  2, 2, 0 |||
  2 |          |          |  1.00000 |  0.64852 | i  |  2, 3, 0 |||
  3 |          |          |  0.71900 |  0.38270 | i  |  2, 4, 0 |||
  4 |          |          |  1.00000 | -0.06907 | i  |  2, 5, 0 |||
  5 |          |          |  0.96900 | -0.89526 | i  |  2, 6, 0 |||
  6 |          |          |  0.71900 |  0.65653 | i  |  2, 7, 0 |||
  7 |          |          |  0.56200 | -0.40446 | i  |  2, 8, 0 |||
  8 |          |          |  1.00000 |  0.54714 | i  |  2, 9, 0 |||
  9 |          |          |  0.50000 |  0.01045 | i  |  2,10, 0 |||
 10 |          |          |  0.00001 | 13.24226 | h  |  5, 2, 0 |||
 11 |          |          |  0.01269 | -2.68737 | h  |  5, 3, 0 |||
 12 |          |          |  0.99792 |  0.51125 | h  |  5, 4, 0 |||
 13 |          |          |  0.99844 |  0.76747 | h  |  5, 5, 0 |||
 14 |          |          |  0.00075 |  1.62307 | o  |  8, 2, 0 |||
----|----------|----------|----------|----------|----|-----------|---
-------|----------|-------

connection definition section :
target | site | source:weight
-------|------|-------------------------------------------------
------------------------------------------------------------
    10 |      |  9: 0.77073,  8:-2.14765,  7:-2.13009,  6: 2.01661,
5:-14.16599,  4:-3.79168,  3:-4.73900,  2:-1.83046,  1:-0.68715
    11 |      |  9:-2.75327,  8: 0.52004,  7: 3.76070,  6: 5.04947,
5:-3.75801,  4:-7.02334,  3: 6.29142,  2: 0.66554,  1:-2.15714
    12 |      |  9: 1.37362,  8: 1.33756,  7:-3.98098,  6:-4.57605,
5: 3.40044,  4: 6.36389,  3:-5.06508,  2: 1.75100,  1: 2.79175
    13 |      |  9: 1.64481,  8: 3.19137,  7:-7.72498,  6:-2.35660,
5:11.08343,  4:-14.47007,  3: 6.59519,  2: 5.97907,  1: 1.44500
    14 |      | 13:-19.50476, 12:10.83345, 11:-11.81212, 10:-
20.42711
-------|------|-------------------------------------------------
------------------------------------------------------------
```

```
SNNS network definition file V1.4-3D

generated at Thu Feb 24 11:45:01 2000

network name : Bstp4

source files :

no. of units : 14
no. of connections : 40
no. of unit types : 0
no. of site types : 0


learning function : Std_Backpropagation
update function   : Topological_Order

unit default section :

act      | bias     | st | subnet | layer | act func     | out func
---------|----------|----|--------|-------|--------------|----------
 0.00000 |  0.00000 | h  |      0 |     1 | Act_Logistic |
Out_Identity
---------|----------|----|--------|-------|--------------|----------

unit definition section :
no. | typeName | unitName | act      | bias     | st | position |
act func | out func | sites
----|----------|----------|----------|----------|----|----------|---
  1 |          |          |  0.96900 | -0.02774 | i  |  2, 2, 0 |||
  2 |          |          |  1.00000 |  0.64852 | i  |  2, 3, 0 |||
  3 |          |          |  0.75000 |  0.38270 | i  |  2, 4, 0 |||
  4 |          |          |  1.00000 | -0.06907 | i  |  2, 5, 0 |||
  5 |          |          |  1.00000 | -0.89526 | i  |  2, 6, 0 |||
  6 |          |          |  1.00000 |  0.65653 | i  |  2, 7, 0 |||
  7 |          |          |  0.64800 | -0.40446 | i  |  2, 8, 0 |||
  8 |          |          |  1.00000 |  0.54714 | i  |  2, 9, 0 |||
  9 |          |          |  0.89100 |  0.01045 | i  |  2,10, 0 |||
 10 |          |          |  0.74325 |  0.15606 | h  |  5, 2, 0 |||
 11 |          |          |  0.13500 | -1.26464 | h  |  5, 3, 0 |||
 12 |          |          |  0.00000 | -6.69597 | h  |  5, 4, 0 |||
 13 |          |          |  1.00000 |  7.30950 | h  |  5, 5, 0 |||
 14 |          |          |  0.00000 | -0.20066 | o  |  8, 2, 0 |||
----|----------|----------|----------|----------|----|----------|---

connection definition section :
target | site | source:weight
-------|------|-------------------------------------------------------
---------------------------------------------------------------
    10 |      |  9: 1.06405,  8: 0.48751,  7: 0.61112,  6:-0.10748,
5:-0.41523,  4:-0.12992,  3: 0.07968,  2: 0.07946,  1:-0.42448
    11 |      |  9: 0.28953,  8: 0.52275,  7:-0.43247,  6: 1.99497,
5:-1.89617,  4: 0.21400,  3:-1.81275,  2:-0.56526,  1: 0.53529
    12 |      |  9: 4.72635,  8:-1.94896,  7: 5.68641,  6: 7.34386,
5:-19.18911,  4:10.90218,  3:-15.21605,  2:-6.24077,  1: 4.22377
    13 |      |  9:-5.55177,  8: 1.68342,  7:-6.17678,  6:-7.99863,
5:20.90612,  4:-11.92016,  3:16.36923,  2: 7.26564,  1:-4.23431
    14 |      | 13:-29.21919, 12:27.01293, 11: 2.86773, 10: 0.59577
-------|------|-------------------------------------------------------
---------------------------------------------------------------
```

```
SNNS network definition file V1.4-3D
generated at Thu Feb 24 14:32:31 2000

network name : Cpck4
source files :
no. of units : 14
no. of connections : 40
no. of unit types : 0
no. of site types : 0


learning function : Std_Backpropagation
update function   : Topological_Order


unit default section :
act       | bias      | st | subnet | layer | act func       | out func
----------|-----------|----|--------|-------|----------------|----------
 0.00000  |  0.00000  | h  |      0 |     1 | Act_Logistic   |
Out_Identity
----------|-----------|----|--------|-------|----------------|----------


unit definition section :

no. | typeName | unitName | act       | bias      | st | position |
act func | out func | sites
----|----------|----------|-----------|-----------|----|----------|---
  1 |          |          |  0.50000  | -0.02774  | i  |  2, 2, 0 |||
  2 |          |          |  0.75000  |  0.64852  | i  |  2, 3, 0 |||
  3 |          |          |  0.50000  |  0.38270  | i  |  2, 4, 0 |||
  4 |          |          |  0.46900  | -0.06907  | i  |  2, 5, 0 |||
  5 |          |          |  0.21900  | -0.89526  | i  |  2, 6, 0 |||
  6 |          |          |  0.46900  |  0.65653  | i  |  2, 7, 0 |||
  7 |          |          |  0.36300  | -0.40446  | i  |  2, 8, 0 |||
  8 |          |          |  0.75000  |  0.54714  | i  |  2, 9, 0 |||
  9 |          |          |  0.50000  |  0.01045  | i  |  2,10, 0 |||
 10 |          |          |  0.92188  |  7.71916  | h  |  5, 2, 0 |||
 11 |          |          |  0.77046  |  7.61043  | h  |  5, 3, 0 |||
 12 |          |          |  0.66374  |  2.26903  | h  |  5, 4, 0 |||
 13 |          |          |  0.00044  |-11.57762  | h  |  5, 5, 0 |||
 14 |          |          |  0.00040  | -1.24719  | o  |  8, 2, 0 |||
----|----------|----------|-----------|-----------|----|----------|---


connection definition section :
target | site | source:weight
-------|------|------------------------------------------------------
----------------------------------------------------------
    10 |      |  9:-1.41646,  8: 0.64922,  7:-3.07085,  6: 0.07015,
5:-11.48549,  4: 4.05031,  3:-4.97808,  2: 2.22001,  1:-5.01612
    11 |      |  9:-1.24439,  8:-1.08055,  7: 0.11892,  6:-0.94654,
5: 5.97719,  4:-7.63271,  3: 0.08967,  2:-2.98732,  1:-0.19953
    12 |      |  9:-1.28501,  8:-0.81584,  7: 1.12058,  6: 1.75455,
5:-0.84752,  4:-4.20182,  3: 2.15160,  2:-1.31434,  1: 1.00386
    13 |      |  9:-1.87308,  8:-1.12816,  7:-2.62228,  6:-1.30780,
5:15.82241,  4: 9.13172,  3: 0.42745,  2: 0.63883,  1:-2.50049
    14 |      | 13:-18.72959, 12: 3.53687, 11: 9.54437, 10:-17.64034
-------|------|------------------------------------------------------
----------------------------------------------------------
```

```
SNNS network definition file V1.4-3D
generated at Fri Feb 18 14:24:40 2000

network name : Pock4
source files :
no. of units : 14
no. of connections : 40
no. of unit types : 0
no. of site types : 0


learning function : Std_Backpropagation
update function   : Topological_Order


unit default section :

act      | bias     | st | subnet | layer | act func     | out func
---------|----------|----|--------|-------|--------------|----------
 0.00000 |  0.00000 | h  |      0 |     1 | Act_Logistic |
Out_Identity
---------|----------|----|--------|-------|--------------|----------


unit definition section :
no. | typeName | unitName | act      | bias     | st | position |
act func | out func | sites
----|----------|----------|----------|----------|----|----------|---
  1 |          |          |  0.00000 |  0.00000 | i  |  2, 2, 0 |||
  2 |          |          |  0.00000 |  0.00000 | i  |  2, 3, 0 |||
  3 |          |          |  0.00000 |  0.00000 | i  |  2, 4, 0 |||
  4 |          |          |  0.12500 |  0.00000 | i  |  2, 5, 0 |||
  5 |          |          |  0.27500 |  0.00000 | i  |  2, 6, 0 |||
  6 |          |          |  0.00000 |  0.00000 | i  |  2, 7, 0 |||
  7 |          |          |  0.00000 |  0.00000 | i  |  2, 8, 0 |||
  8 |          |          |  0.00000 |  0.00000 | i  |  2, 9, 0 |||
  9 |          |          |  0.00000 |  0.00000 | i  |  2,10, 0 |||
 10 |          |          |  0.30629 |  0.28464 | h  |  5, 2, 0 |||
 11 |          |          |  0.30629 |  0.28464 | h  |  5, 3, 0 |||
 12 |          |          |  0.30629 |  0.28464 | h  |  5, 4, 0 |||
 13 |          |          |  0.30629 |  0.28464 | h  |  5, 5, 0 |||
 14 |          |          |  0.98647 | 17.26874 | o  |  8, 2, 0 |||
----|----------|----------|----------|----------|----|----------|---


connection definition section :
target | site | source:weight
-------|------|---------------------------------------------------------
-------------------------------------------------------------
    10 |      |  9: 5.40527,  8: 6.92004,  7:-2.64120,  6:-1.90457,
5:-4.17318,  4: 0.36294,  3: 5.39208,  2: 7.19914,  1: 5.06442
    11 |      |  9: 5.40527,  8: 6.92004,  7:-2.64120,  6:-1.90457,
5:-4.17318,  4: 0.36294,  3: 5.39208,  2: 7.19914,  1: 5.06442
    12 |      |  9: 5.40527,  8: 6.92004,  7:-2.64120,  6:-1.90457,
5:-4.17318,  4: 0.36294,  3: 5.39208,  2: 7.19914,  1: 5.06442
    13 |      |  9: 5.40527,  8: 6.92004,  7:-2.64120,  6:-1.90457,
5:-4.17318,  4: 0.36294,  3: 5.39208,  2: 7.19914,  1: 5.06442
    14 |      | 13:-10.59404, 12:-10.59404, 11:-10.59404, 10:-
10.59404
-------|------|---------------------------------------------------------
-------------------------------------------------------------
```

```
SNNS network definition file V1.4-3D
generated at Fri Feb 18 11:31:36 2000

network name : prot4
source files :
no. of units : 14
no. of connections : 40
no. of unit types : 0
no. of site types : 0


learning function : Std_Backpropagation
update function   : Topological_Order


unit default section :
act      | bias     | st | subnet | layer | act func     | out func
---------|----------|----|--------|-------|--------------|----------
 0.00000 |  0.00000 | h  |      0 |     1 | Act_Logistic |
Out_Identity
---------|----------|----|--------|-------|--------------|----------


unit definition section :
no. | typeName | unitName | act      | bias     | st | position |
act func | out func | sites
----|----------|----------|----------|----------|----|----------|---
  1 |          |          |  0.00000 |  0.00000 | i  |  2, 2, 0 |||
  2 |          |          |  0.09400 |  0.00000 | i  |  2, 3, 0 |||
  3 |          |          |  0.00000 |  0.00000 | i  |  2, 4, 0 |||
  4 |          |          |  0.34400 |  0.00000 | i  |  2, 5, 0 |||
  5 |          |          |  0.00000 |  0.00000 | i  |  2, 6, 0 |||
  6 |          |          |  0.32500 |  0.00000 | i  |  2, 7, 0 |||
  7 |          |          |  0.00000 |  0.00000 | i  |  2, 8, 0 |||
  8 |          |          |  0.09400 |  0.00000 | i  |  2, 9, 0 |||
  9 |          |          |  0.00000 |  0.00000 | i  |  2,10, 0 |||
 10 |          |          |  1.00000 | 10.91404 | h  |  5, 2, 0 |||
 11 |          |          |  1.00000 | 10.91404 | h  |  5, 3, 0 |||
 12 |          |          |  1.00000 | 10.91404 | h  |  5, 4, 0 |||
 13 |          |          |  1.00000 | 10.91404 | h  |  5, 5, 0 |||
 14 |          |          |  0.00000 | 21.10520 | o  |  8, 2, 0 |||
----|----------|----------|----------|----------|----|----------|---


connection definition section :
target | site | source:weight
-------|------|-----------------------------------------------------
------------------------------------------------------------------
    10 |      |  9:-1.70298,  8: 0.53472,  7:-11.72635,  6: 5.53218,
5:-0.51053,  4: 7.75667,  3:-12.05967,  2: 0.67843,  1:-0.49372
    11 |      |  9:-1.70298,  8: 0.53472,  7:-11.72635,  6: 5.53218,
5:-0.51053,  4: 7.75667,  3:-12.05967,  2: 0.67843,  1:-0.49372
    12 |      |  9:-1.70298,  8: 0.53472,  7:-11.72635,  6: 5.53218,
5:-0.51053,  4: 7.75667,  3:-12.05967,  2: 0.67843,  1:-0.49372
    13 |      |  9:-1.70298,  8: 0.53472,  7:-11.72635,  6: 5.53218,
5:-0.51053,  4: 7.75667,  3:-12.05967,  2: 0.67843,  1:-0.49372
    14 |      | 13:-13.81524, 12:-13.81524, 11:-13.81524, 10:-
13.81524
-------|------|-----------------------------------------------------
------------------------------------------------------------------
```

```
SNNS network definition file V1.4-3D
generated at Wed Feb 02 10:13:59 2000

network name : protru4
source files :
no. of units : 14
no. of connections : 40
no. of unit types : 0
no. of site types : 0


learning function : Std_Backpropagation
update function   : Topological_Order


unit default section :
act      | bias      | st | subnet | layer | act func      | out func
---------|-----------|----|--------|-------|---------------|----------
 0.00000 |  0.00000  | h  |      0 |     1 | Act_Logistic  |
Out_Identity
---------|-----------|----|--------|-------|---------------|----------


unit definition section :
no. | typeName | unitName | act      | bias     | st | position |
act func | out func | sites
----|----------|----------|----------|----------|----|----------|---
   1 |          |          | 0.50000 | -0.02774 | i  |  2, 2, 0 |||
   2 |          |          | 1.00000 |  0.64852 | i  |  2, 3, 0 |||
   3 |          |          | 0.66300 |  0.38270 | i  |  2, 4, 0 |||
   4 |          |          | 1.00000 | -0.06907 | i  |  2, 5, 0 |||
   5 |          |          | 0.96900 | -0.89526 | i  |  2, 6, 0 |||
   6 |          |          | 0.71900 |  0.65653 | i  |  2, 7, 0 |||
   7 |          |          | 0.56200 | -0.40446 | i  |  2, 8, 0 |||
   8 |          |          | 1.00000 |  0.54714 | i  |  2, 9, 0 |||
   9 |          |          | 0.50000 |  0.01045 | i  |  2,10, 0 |||
  10 |          |          | 0.99592 |  8.38474 | h  |  5, 2, 0 |||
  11 |          |          | 0.00314 | -8.49232 | h  |  5, 3, 0 |||
  12 |          |          | 0.05516 | -0.85585 | h  |  5, 4, 0 |||
  13 |          |          | 0.99998 | 13.37167 | h  |  5, 5, 0 |||
  14 |          |          | 0.00000 |  5.78599 | o  |  8, 2, 0 |||
----|----------|----------|----------|----------|----|----------|---


connection definition section :
target | site | source:weight
-------|------|-------------------------------------------------------
---------------------------------------------------------------
    10 |      |  9:-0.98914,  8: 0.57930,  7:-8.50600,  6: 4.72343,
5:-0.72822,  4: 5.14143,  3:-8.53917,  2: 0.16175,  1:-1.04795
    11 |      |  9: 1.46840,  8: 0.62940,  7: 9.07015,  6:-4.77817,
5: 0.31307,  4:-6.52959,  3: 8.52381,  2: 0.06935,  1: 0.42396
    12 |      |  9:-0.86106,  8:-0.75812,  7:-0.71317,  6:-0.32967,
5:-0.60433,  4:-0.24696,  3: 0.17162,  2: 0.24922,  1: 0.62218
    13 |      |  9:-2.77311,  8: 1.45126,  7:-17.00005,  6: 9.15429,
5: 0.26303,  4: 8.79558,  3:-14.70441,  2: 1.72575,  1:-0.85702
    14 |      | 13:-17.84623, 12:-0.36849, 11:13.20347, 10:-9.72393
-------|------|-------------------------------------------------------
---------------------------------------------------------------
```

```
SNNS network definition file V1.4-3D
generated at Tue Feb 22 11:08:35 2000

network name : slot4
source files :
no. of units : 14
no. of connections : 40
no. of unit types : 0
no. of site types : 0


learning function : Std_Backpropagation
update function   : Topological_Order


unit default section :
act      | bias     | st | subnet | layer | act func     | out func
---------|----------|----|--------|-------|--------------|----------
 0.00000 |  0.00000 | h  |      0 |     1 | Act_Logistic |
Out_Identity
---------|----------|----|--------|-------|--------------|----------


unit definition section :
no. | typeName | unitName | act      | bias     | st | position |
act func | out func | sites
----|----------|----------|----------|----------|----|----------|---
  1 |          |          |  0.12500 | -0.02774 | i  |  2, 2, 0 |||
  2 |          |          |  1.00000 |  0.64852 | i  |  2, 3, 0 |||
  3 |          |          |  0.53100 |  0.38270 | i  |  2, 4, 0 |||
  4 |          |          |  1.00000 | -0.06907 | i  |  2, 5, 0 |||
  5 |          |          |  0.89100 | -0.89526 | i  |  2, 6, 0 |||
  6 |          |          |  0.66300 |  0.65653 | i  |  2, 7, 0 |||
  7 |          |          |  0.50000 | -0.40446 | i  |  2, 8, 0 |||
  8 |          |          |  0.89100 |  0.54714 | i  |  2, 9, 0 |||
  9 |          |          |  0.50000 |  0.01045 | i  |  2,10, 0 |||
 10 |          |          |  0.00621 | 10.80250 | h  |  5, 2, 0 |||
 11 |          |          |  0.86571 |  6.78798 | h  |  5, 3, 0 |||
 12 |          |          |  0.08383 |  1.26672 | h  |  5, 4, 0 |||
 13 |          |          |  0.99116 |  4.91716 | h  |  5, 5, 0 |||
 14 |          |          |  0.00003 |  3.48763 | o  |  8, 2, 0 |||
----|----------|----------|----------|----------|----|----------|---


connection definition section :
target | site | source:weight
-------|------|-----------------------------------------------------
---------------------------------------------------------------
    10 |      |  9:-8.41061,  8:-0.92315,  7: 9.38255,  6:-1.85716,
5:-27.79278,  4:15.42916,  3:-7.34539,  2: 0.21249,  1:-10.30368
    11 |      |  9:-0.00619,  8: 0.18006,  7:-0.73655,  6: 2.26402,
5: 8.61059,  4:-12.04490,  3:-1.30277,  2:-1.16905,  1: 0.15318
    12 |      |  9:-1.85079,  8:-1.36491,  7:-0.34164,  6:-0.62627,
5:-1.13934,  4: 0.10491,  3:-0.11626,  2: 0.04946,  1:-0.06450
    13 |      |  9: 2.69754,  8:-3.09200,  7:-11.28075,  6:-
27.01808,  5: 8.11850,  4: 4.95423,  3:11.95701,  2: 5.38919,  1:
6.68390
    14 |      | 13:-23.63280, 12:-2.72311, 11:11.23320, 10:-24.89463
-------|------|-----------------------------------------------------
---------------------------------------------------------------
```

```
SNNS network definition file V1.4-3D
generated at Thu Feb 24 10:35:06 2000

network name : Step4
source files :
no. of units : 14
no. of connections : 40
no. of unit types : 0
no. of site types : 0


learning function : Std_Backpropagation
update function   : Topological_Order


unit default section :
act      | bias     | st | subnet | layer | act func     | out func
---------|----------|----|--------|-------|--------------|----------
 0.00000 |  0.00000 | h  |      0 |     1 | Act_Logistic |
Out_Identity
---------|----------|----|--------|-------|--------------|----------


unit definition section :
no. | typeName | unitName | act      | bias     | st | position |
act func | out func | sites
----|----------|----------|----------|----------|----|----------|---
  1 |          |          |  0.62500 | -0.02774 | i  |  2, 2, 0 |||
  2 |          |          |  0.75000 |  0.64852 | i  |  2, 3, 0 |||
  3 |          |          |  0.87500 |  0.38270 | i  |  2, 4, 0 |||
  4 |          |          |  1.00000 | -0.06907 | i  |  2, 5, 0 |||
  5 |          |          |  1.00000 | -0.89526 | i  |  2, 6, 0 |||
  6 |          |          |  1.00000 |  0.65653 | i  |  2, 7, 0 |||
  7 |          |          |  0.50000 | -0.40446 | i  |  2, 8, 0 |||
  8 |          |          |  0.62500 |  0.54714 | i  |  2, 9, 0 |||
  9 |          |          |  0.50000 |  0.01045 | i  |  2,10, 0 |||
 10 |          |          |  0.82391 |  3.50203 | h  |  5, 2, 0 |||
 11 |          |          |  0.52999 | -1.07883 | h  |  5, 3, 0 |||
 12 |          |          |  0.00114 | -5.24504 | h  |  5, 4, 0 |||
 13 |          |          |  0.99994 |  6.83973 | h  |  5, 5, 0 |||
 14 |          |          |  0.00000 |  1.67919 | o  |  8, 2, 0 |||
----|----------|----------|----------|----------|----|----------|---


connection definition section :
target | site | source:weight
-------|------|-----------------------------------------------------
-----------------------------------------------------------------
    10 |      |  9:-3.60035,  8: 0.47451,  7: 0.92783,  6:-0.36991,
5: 0.00604,  4: 1.04670,  3:-0.16096,  2: 0.13584,  1:-2.50106
    11 |      |  9: 1.25999,  8: 0.83639,  7:-0.34471,  6: 0.70730,
5:-0.00252,  4:-1.05903,  3:-0.09475,  2: 0.29627,  1: 0.69361
    12 |      |  9: 9.06608,  8:-1.63431,  7:-2.17845,  6: 0.57245,
5:-2.82450,  4:-2.73192,  3:-1.22282,  2:-0.85207,  1: 4.38325
    13 |      |  9:-12.01768,  8: 1.50089,  7: 1.40984,  6: 0.04922,
5: 4.33732,  4: 3.21240,  3: 1.78812,  2: 2.03572,  1:-5.46880
    14 |      | 13:-15.30683, 12:12.66523, 11: 3.12786, 10:-5.25481
-------|------|-----------------------------------------------------
-----------------------------------------------------------------
```

```
NNS network definition file V1.4-3D
generated at Thu Feb 24 15:25:20 2000

network name : thol4
source files :
no. of units : 14
no. of connections : 40
no. of unit types : 0
no. of site types : 0


learning function : Std_Backpropagation
update function   : Topological_Order


unit default section :
act      | bias     | st | subnet | layer | act func     | out func
---------|----------|----|--------|-------|--------------|----------
 0.00000 |  0.00000 | h  |      0 |     1 | Act_Logistic |
Out_Identity
---------|----------|----|--------|-------|--------------|----------


unit definition section :
no. | typeName | unitName | act      | bias     | st | position |
act func | out func | sites
----|----------|----------|----------|----------|----|----------|---
  1 |          |          |  0.53100 | -0.21440 | i  |  2, 2, 0 |||
  2 |          |          |  1.00000 | -0.08751 | i  |  2, 3, 0 |||
  3 |          |          |  0.89100 | -0.79513 | i  |  2, 4, 0 |||
  4 |          |          |  1.00000 |  0.33135 | i  |  2, 5, 0 |||
  5 |          |          |  0.62500 | -0.12518 | i  |  2, 6, 0 |||
  6 |          |          |  0.89100 | -0.06791 | i  |  2, 7, 0 |||
  7 |          |          |  0.25000 |  0.16790 | i  |  2, 8, 0 |||
  8 |          |          |  1.00000 | -0.07233 | i  |  2, 9, 0 |||
  9 |          |          |  0.53100 |  0.85214 | i  |  2,10, 0 |||
 10 |          |          |  0.00001 |  8.72640 | h  |  5, 2, 0 |||
 11 |          |          |  0.95536 |  0.37047 | h  |  5, 3, 0 |||
 12 |          |          |  0.99999 | -6.47770 | h  |  5, 4, 0 |||
 13 |          |          |  0.19754 |  1.19868 | h  |  5, 5, 0 |||
 14 |          |          |  0.00000 |  4.51606 | o  |  8, 2, 0 |||
----|----------|----------|----------|----------|----|----------|---


connection definition section :
target | site | source:weight
-------|------|-------------------------------------------------
---------------------------------------------------------------
    10 |      |  9: 2.15692,  8: 0.20187,  7:-0.28246,  6:-11.10997,
5: 2.98953,  4:-12.61870,  3:-3.43427,  2: 1.69505,  1: 0.88706
    11 |      |  9: 0.90278,  8: 1.54694,  7:-2.88078,  6:-0.41426,
5: 9.72734,  4: 1.34382,  3:-9.26966,  2: 3.52175,  1:-1.75114
    12 |      |  9:-1.95321,  8: 0.69462,  7:-6.16589,  6: 7.04293,
5: 8.81587,  4:13.56495,  3:-5.12291,  2: 1.34045,  1:-3.15303
    13 |      |  9:-0.28075,  8: 1.97101,  7: 1.42938,  6:-2.57236,
5:-4.14600,  4:-5.78865,  3: 4.68488,  2: 0.14496,  1: 2.96233
    14 |      | 13: 8.29476, 12:-16.23826, 11:-12.39637, 10:-
18.46541
-------|------|-------------------------------------------------
---------------------------------------------------------------
```

Appendix 2. Result file of Neural Network Recognition Process.

Sample part real1.sat
Result file: part1_slot4.res.

SNNS result file V1.4-3D
generated at Tue Feb 22 11:09:31 2000

No. of patterns : 166
No. of input units : 9
No. of output units : 1
startpattern : 1
endpattern : 166
input patterns included
#1.1
0.5 0.5 0.5 0.62 0.125 0.365 0.5 0.5 0.5
0
#2.1
0.5 0.5 0.5 0.567 0.125 0.356 0.5 0.5 0.5
0
#3.1
0.5 0.5 0.5 0.567 0.125 0.356 0.5 0.5 0.5
0
#4.1
0.5 0.375 0.567 0.859 0.469 0.719 0.125 0.5 0.5
0
#5.1
0.125 1 0.5 1 0.859 0.567 0.469 0.891 0.5
0.00001
#6.1
0.5 0.125 0.469 0.567 0.719 0.469 0.375 0.125 0.5
0.00007
#7.1
0.5 0.62 0.859 1 1 0.891 0.5 0.567 0.5
0.00009
#8.1
0.5 0.5 0.567 0.859 0.469 0.719 0.125 0.375 0.5
0
#9.1
0.891 1 0.62 1 1 1 0.567 0.891 0.859
0.00031
#10.1
0.125 1 0.5 1 0.859 0.567 0.469 0.859 0.5
0.00001
#11.1
0.567 0.625 0.891 1 1 1 0.5 0.62 0.5
0.00042
#12.1
0.5 0.62 0.859 1 1 0.859 0.5 0.567 0.5
0.00007
#13.1
0.891 1 0.625 1 1 1 0.567 1 0.891
0.0004
#14.1
0.859 1 0.62 1 1 1 0.567 0.969 0.859
0.0006
#15.1
0.567 0.654 0.891 1 1 1 0.5 0.625 0.5
0.00034
#16.1
0.567 0.719 0.969 1 1 1 0.5 0.62 0.5
0.00011
#17.1
0.969 1 0.654 1 1 1 0.567 1 0.891
0.00017
#18.1
0.969 1 0.719 1 1 1 0.567 1 0.969
0.00011
#19.1
0.567 0.719 0.969 1 1 1 0.5 0.654 0.5
0.00012
#20.1
1 1 0.969 1 0.654 1 0.969 1 1
0.00211
#21.1
0.25 1 0.625 1 0.891 0.654 0.531 1 0.5
0.00002
#22.1
0.531 1 0.891 1 0.625 0.891 0.25 1 0.531
0
#23.1
0.25 1 0.62 1 0.891 0.625 0.531 1 0.5
0.00002
#24.1
0.125 1 0.531 1 0.891 0.62 0.5 0.859 0.5
0.00002
#25.1
0.469 1 0.125 0.891 0.5 0.859 0.125 0.531 0
0
#26.1
0.125 0.859 0.5 0.375 0.125 0 0.469 0.719 0
0
#27.1
1 1 1 1 0.567 1 1 1 1
0.01398
#28.1
0.5 1 0.654 1 0.969 0.719 0.562 1 0.5
0.00005
#29.1
0.5 1 0.62 1 0.969 0.719 0.562 1 0.5
0.00005
#30.1
1 1 1 1 0.62 1 0.969 1 1
0.00051
#31.1
0.5 0 0.344 0.562 0.094 0.365 0 0 0.5
0
#32.1
0.344 0.365 0 0.094 0 0 0.5 0.356 0.5
0
#33.1
0 0.094 0 0.356 0 0.344 0 0.094 0
0
#34.1
0.344 0.365 0 0.094 0 0 0.5 0.356 0.5
0
#35.1
0.5 0 0.344 0.562 0.094 0.365 0 0 0.5
0
#36.1
0 0 0.469 0.562 0.365 0.469 0.469 0 0
0
#37.1
0.094 0.109 0 0.365 0 0.356 0 0.109 0
0
#38.1
0 0 0.469 0.875 0.356 0.469 0.219 0 0
0
#39.1
0 0.109 0 0.365 0 0.356 0 0.094 0

0
#40.1
0 0 0.469 0.562 0.365 0.469 0.469 0 0
0
#41.1
0.5 1 0.654 1 0.969 0.719 0.562 0.891 0.5
0.00005
#42.1
0.625 0.719 0.891 1 1 0.969 0.5 0.654 0.5
0.00011
#43.1
0.891 0.969 0.719 1 1 1 0.625 0.969 0.891
0.00024
#44.1
0.62 0.719 0.891 1 1 0.969 0.5 0.625 0.5
0.0001
#45.1
0.5 1 0.62 1 0.969 0.719 0.562 0.891 0.5
0.00005
#46.1
0.531 1 0.891 1 0.625 0.891 0.25 1 0.531
0
#47.1
0.25 1 0.625 1 0.891 0.654 0.531 0.969 0.5
0.00002
#48.1
0.5 0.109 0.344 0.562 0.094 0.365 0 0 0.5
0
#49.1
0.344 0.375 0 0.109 0 0.094 0.5 0.365 0.5
0
#50.1
0.094 0.109 0 0.375 0 0.344 0 0.109 0.094
0
#51.1
0.344 0.375 0 0.109 0 0.094 0.5 0.365 0.5
0
#52.1
0.5 0.109 0.344 0.562 0.094 0.365 0 0 0.5
0
#53.1
0 0.75 0.365 0.469 0.109 0.375 0 0.094 0.5
0
#54.1
0 0.469 0.109 0.75 0.375 0.109 0 0.469 0
0
#55.1
0 0.75 0.365 0.469 0.109 0.375 0 0.094 0.5
0
#56.1
0.25 0.375 0 0.109 0 0 0.5 0.365 0.5
0
#57.1
0 0.109 0 0.375 0 0.25 0 0.109 0
0
#58.1
0 0.109 0 0.365 0 0.25 0 0.109 0
0
#59.1
0.25 0.375 0 0.109 0 0 0.5 0.365 0.5
0
#60.1
0.25 0.375 0 0.109 0 0 0.5 0.365 0.5
0
#61.1
0 0.109 0 0.365 0 0.25 0 0.109 0
0
#62.1
0 0.109 0 0.375 0 0.25 0 0.109 0
0
#63.1
0.25 0.375 0 0.109 0 0 0.5 0.365 0.5
0
#64.1
0 0.469 0.109 0.75 0.375 0.109 0 0.469 0
0
#65.1
0 0.75 0.365 0.469 0.109 0.375 0 0 0.5
0
#66.1
0 0.75 0.365 0.469 0.109 0.375 0 0 0.5
0
#67.1
0 0 0 0 0.25 0 0 0 0
0
#68.1
0.625 0.75 0.891 1 1 1 0.5 0.654 0.5
0.00015
#69.1
0.891 1 0.75 1 1 1 0.654 1 0.891
0.00021
#70.1
0.891 1 0.75 1 1 1 0.625 1 0.891
0.00017
#71.1
0.625 0.75 0.891 1 1 1 0.5 0.654 0.5
0.00015
#72.1
0.62 0.75 0.891 1 1 1 0.5 0.625 0.5
0.00014
#73.1
0.891 1 0.75 1 1 1 0.625 1 0.891
0.00017
#74.1
0.891 1 0.75 1 1 1 0.62 1 0.891
0.00016
#75.1
0.62 0.75 0.891 1 1 1 0.5 0.625 0.5
0.00014
#76.1
0.531 1 0.891 1 0.625 0.891 0.25 1 0.531
0
#77.1
0.25 1 0.625 1 0.891 0.654 0.531 1 0.5
0.00002
#78.1
0.25 1 0.625 1 0.891 0.654 0.531 1 0.5
0.00002
#79.1
1 1 1 1 0.75 1 1 1 1
0.00036
#80.1
0.5 0.625 0.654 0.891 0.531 0.891 0.25 0.625 0.5
0.00876
#81.1
0.891 0.891 0.531 0.625 0.25 0.625 0.531 0.891 0.891
0.00001
#82.1
0.531 1 0.891 1 0.625 0.891 0.25 1 0.531
0
#83.1
0.5 0.375 0.109 0.75 0.469 0.365 0.109 0.375 0.5
0

#84.1
0 0.75 0.365 0.469 0.109 0.375 0 0 0.5
0
#85.1
0.109 0.109 0.375 0.469 0.75 0.469 0.375 0.109 0.109
0.00041
#86.1
0.5 0 0.094 0.562 0.344 0.094 0 0 0.5
0
#87.1
0.5 0.375 0.109 0.75 0.469 0.365 0.109 0.375 0.5
0
#88.1
0 0.469 0.109 0.75 0.375 0.109 0 0.469 0
0
#89.1
0.25 1 0.62 1 0.891 0.625 0.531 0.969 0.5
0.00002
#90.1
0.5 0.625 0.62 0.891 0.531 0.891 0.25 0.625 0.5
0.07651
#91.1
0.25 1 0.62 1 0.891 0.625 0.531 1 0.5
0.00002
#92.1
0.5 0.625 0.654 0.891 0.531 0.781 0.25 0.5 0.5
0
#93.1
0.5 0.25 0.531 0.654 0.781 0.531 0.5 0.25 0.5
0.00008
#94.1
0.5 0.625 0.654 0.891 0.531 0.781 0.25 0.5 0.5
0
#95.1
0.781 0.891 0.531 0.625 0.25 0.531 0.5 0.891 0.781
0
#96.1
0.531 0.531 0.25 0.781 0.5 0.781 0.25 0.531 0.531
0.99967
#97.1
0.781 0.891 0.531 0.625 0.25 0.531 0.5 0.891 0.781
0
#98.1
0 0.75 0.365 0.469 0.109 0.375 0 0 0.5
0
#99.1
0.5 0.375 0.219 0.75 0.469 0.365 0.109 0.5 0.5
0
#100.1
0.5 0.75 0.5 0.469 0.219 0.469 0.365 0.75 0.5
0
#101.1
0.5 0.5 0.219 0.75 0.469 0.365 0.109 0.375 0.5
0
#102.1
0 0.75 0.365 0.469 0.109 0.375 0 0 0.5
0
#103.1
0.356 0.375 0 0.109 0 0 0.5 0.365 0.5
0
#104.1
0 0.109 0 0.375 0 0.356 0 0.109 0
0
#105.1
0 0.469 0.109 0.75 0.375 0.109 0 0.469 0
0
#106.1
0.109 0.219 0.5 0.469 0.75 0.469 0.375 0.219 0.109
0.00007
#107.1
0.469 0.469 0.219 0.75 0.5 0.75 0.219 0.469 0.469
0.99827
#108.1
0.109 0.219 0.375 0.469 0.75 0.469 0.5 0.219 0.109
0.01529
#109.1
0.5 0.375 0.219 0.75 0.469 0.365 0.109 0.5 0.5
0
#110.1
0.5 0.75 0.5 0.469 0.219 0.469 0.365 0.75 0.5
0
#111.1
0.5 0.5 0.219 0.75 0.469 0.365 0.109 0.375 0.5
0
#112.1
0 0.75 0.365 0.469 0.109 0.375 0 0 0.5
0
#113.1
0.356 0.375 0 0.109 0 0 0.5 0.365 0.5
0
#114.1
0.109 0.109 0 0.365 0 0.356 0 0.109 0
0
#115.1
0.25 1 0.62 1 0.891 0.625 0.531 1 0.5
0.00002
#116.1
0.5 0.625 0.62 0.891 0.531 0.781 0.25 0.5 0.5
0
#117.1
0.5 0.25 0.531 0.62 0.781 0.531 0.5 0.25 0.5
0.00008
#118.1
0.5 0.625 0.62 0.891 0.531 0.781 0.25 0.5 0.5
0
#119.1
0.356 0.5 0 0.109 0 0.109 0.5 0.365 0.5
0
#120.1
0 0.875 0.356 0.5 0.109 0.469 0 0.109 0.5
0
#121.1
0.5 0.625 0.219 0.875 0.469 0.356 0.109 0.5 0.5
0
#122.1
0.5 0.875 0.469 0.625 0.219 0.469 0.356 0.875 0.5
0
#123.1
0.5 0.625 0.219 0.875 0.469 0.356 0.109 0.5 0.5
0
#124.1
0 0.875 0.356 0.469 0.109 0.5 0 0.109 0.5
0
#125.1
0.356 0.5 0 0.109 0 0.109 0.5 0.365 0.5
0
#126.1
0.469 1 0.109 0.875 0.5 0.875 0.109 0.469 0
0

#127.1
0.219 1 0.469 1 0.875 0.625 0.5 0.875 0.109
0
#128.1
0.469 1 0.875 1 0.625 0.875 0.219 1 0.469
0
#129.1
0.219 1 0.5 1 0.875 0.625 0.469 0.875 0.109
0
#130.1
0.469 1 0.109 0.875 0.5 0.875 0.109 0.469 0
0
#131.1
0 0.875 0.365 0.5 0.109 0.469 0 0.109 0.5
0
#132.1
0.5 0.625 0.875 1 1 0.875 0.5 0.625 0.5
0.00008
#133.1
0.875 0.875 0.625 1 1 1 0.625 0.875 0.875
0.00467
#134.1
0.5 0.625 0.875 1 1 0.875 0.5 0.625 0.5
0.00008
#135.1
0.5 0.625 0.219 0.875 0.469 0.365 0.109 0.5 0.5
0
#136.1
0.5 0.875 0.469 0.625 0.219 0.469 0.365 0.875 0.5
0
#137.1
0.5 0.625 0.219 0.875 0.469 0.365 0.109 0.5 0.5
0
#138.1
0 0.875 0.365 0.5 0.109 0.469 0 0.109 0.5
0
#139.1
0.219 1 0.5 1 0.875 0.625 0.469 0.875 0.109
0
#140.1
0.219 1 0.5 1 0.875 0.625 0.469 0.875 0.109
0
#141.1
0.5 0.375 0.62 0.891 0.531 0.75 0.125 0.5 0.5
0.00001
#142.1
0.5 0.125 0.469 0.62 0.75 0.531 0.375 0.125 0.5
0.00007
#143.1
0.5 0.375 0.62 0.859 0.469 0.75 0.125 0.5 0.5
0
#144.1
0.125 1 0.5 1 0.859 0.62 0.469 0.859 0.5
0.00001
#145.1
0.125 0.859 0.469 0 0.125 0.5 0.375 0.719 0
0
#146.1
0.375 0.375 0 0.125 0 0.125 0.5 0.5 0.5
0
#147.1
0.125 0.125 0 0.375 0 0.375 0 0.125 0.125
0
#148.1
0.5 0.375 0 0.125 0 0.125 0.5 0.375 0.5
0
#149.1
0 0.469 0.125 0.719 0.375 0.125 0 0.469 0
0
#150.1
0.125 0.891 0 0.531 0.125 0.375 0.5 0.75 0
0
#151.1
0.125 0.859 0.5 0.375 0.125 0 0.469 0.75 0
0
#152.1
0 0.531 0.125 0.75 0.375 0.125 0 0.469 0
0
#153.1
0.5 0.5 0.5 0.75 0.875 0.625 0.5 0.5 0.5
0.0001
#154.1
0.5 0.5 0.5 0.875 0.75 0.125 0.5 0.5 0.5
0.00001
#155.1
0.5 0.5 0.5 0.875 0.625 0.5 0.5 0.5 0.5
0
#156.1
0.5 0.5 0.5 0.375 0.125 0.25 0.5 0.5 0.5
0
#157.1
0.5 0.5 0.5 0.875 0.25 0.125 0.5 0.5 0.5
0
#158.1
0.5 0.5 0.5 0.125 0.375 0.5 0.5 0.5 0.5
0.01411
#159.1
0.5 0.5 0.5 0.75 0.125 0.567 0.5 0.5 0.5
0
#160.1
0.5 0.5 0.5 0.356 0.875 0.25 0.5 0.5 0.5
0.00009
#161.1
0.469 1 0.125 0.859 0.5 0.859 0.125 0.469 0
0
#162.1
0.469 1 0.875 1 0.625 0.875 0.219 1 0.469
0
#163.1
0.5 0 0.094 0.562 0.344 0.094 0 0 0.5
0
#164.1
0.5 1 0.969 1 0.719 0.969 0.562 1 0.5
0.00006
#165.1
0.5 1 0.969 1 0.719 0.969 0.562 1 0.5
0.00006
#166.1
0.5 0.5 0.969 0.969 0.562 0.969 0.969 0.5 0.5
0

Appendix 3. Sample SAT file

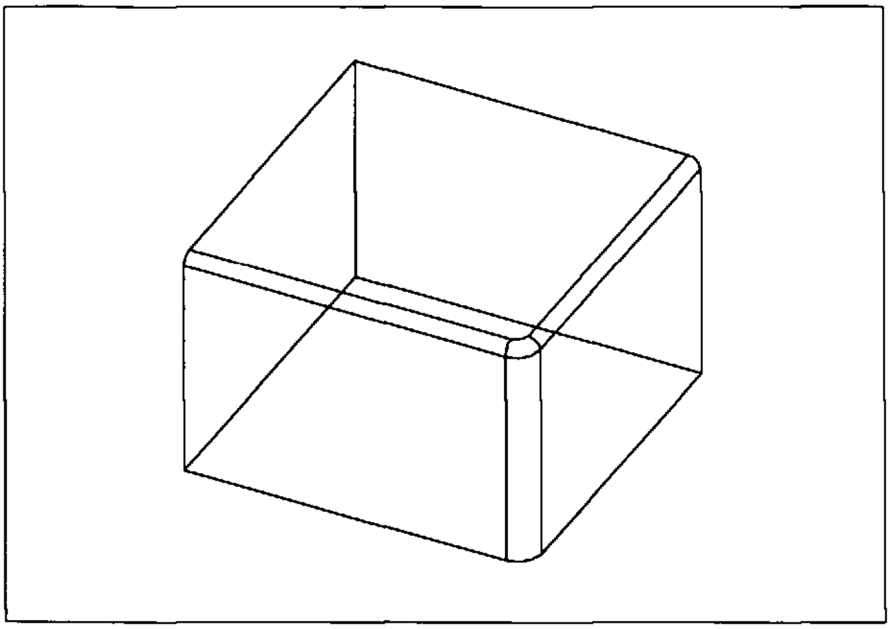

Figure 69. Box1.sat

```
HEADER 106 213 1 0
0. body $-1 $1 $-1 $-1 #
1. lump $-1 $-1 $2 $0 #
2. shell $-1 $-1 $-1 $3 $1 #
3. face $4 $5 $6 $2 $-1 $7 forward single #
4. color-adesk-attrib $-1 $-1 $-1 $3 256 #
5. face $8 $9 $10 $2 $-1 $11 forward single #
6. loop $-1 $-1 $12 $3 #
7. cone-surface $13 -40.894024639034562 -181.05488688355484 -5 0 -1
   0 3.5355339059327329 0 3.5355339059327431 1 I I 0 1 0 I I I I #
8. color-adesk-attrib $-1 $-1 $-1 $5 256 #
9. face $14 $15 $16 $2 $-1 $17 forward single #
10.loop $-1 $-1 $18 $5 #
11.torus-surface $19 -45.894024639034569 -208.55488688355484 -5 0 0
   -1 5 5 -1 0 0 0 I I I I #
12.coedge $-1 $20 $21 $22 $23 0 $6 $-1 #
13.SURFACE_ID-Designer-attrib $-1 $-1 $-1 $7 1 0 #
14.color-adesk-attrib $-1 $-1 $-1 $9 256 #
15.face $24 $25 $26 $2 $-1 $27 reversed single #
16.loop $-1 $-1 $28 $9 #
17.cone-surface $29 -148.3940246390346 -213.55488688355484 -5 -1 0 0
   0 -3.5355339059327373 3.5355339059327373 1 I I 0 1 0 I I I I #
18.coedge $-1 $30 $31 $32 $33 0 $10 $-1 #
19.SURFACE_ID-Designer-attrib $-1 $-1 $-1 $11 2 0 #
20.coedge $-1 $34 $12 $31 $35 1 $6 $-1 #
21.coedge $-1 $12 $34 $36 $37 0 $6 $-1 #
22.coedge $-1 $38 $32 $12 $23 1 $26 $-1 #
23.edge $39 $40 $41 $22 $42 0 #
```

```
24.color-adesk-attrib $-1 $-1 $-1 $15 256 #
25.face $43 $44 $45 $2 $-1 $46 forward single #
26.loop $-1 $-1 $47 $15 #
27.plane-surface $48 -110.89402463903458 -143.55488688355484 0 0 0 -
   1 -1 0 0 0 I I I I #
28.coedge $-1 $49 $50 $51 $52 0 $16 $-1 #
29.SURFACE_ID-Designer-attrib $-1 $-1 $-1 $17 3 0 #
30.coedge $-1 $53 $18 $49 $54 1 $10 $-1 #
31.coedge $-1 $18 $53 $20 $35 0 $10 $-1 #
32.coedge $-1 $22 $47 $18 $33 1 $26 $-1 #
33.edge $55 $41 $56 $32 $57 0 #
34.coedge $-1 $21 $20 $58 $59 0 $6 $-1 #
35.edge $60 $61 $41 $31 $62 0 #
36.coedge $-1 $63 $64 $21 $37 1 $45 $-1 #
37.edge $65 $66 $40 $36 $67 0 #
38.coedge $-1 $68 $22 $64 $69 1 $26 $-1 #
39.color-adesk-attrib $-1 $-1 $-1 $23 256 #
40.vertex $-1 $69 $70 #
41.vertex $-1 $23 $71 #
42.straight-curve $72 -40.894024639034562 -181.05488688355484 0 0 -1
   0 F -128 F 43 #
43.color-adesk-attrib $-1 $-1 $-1 $25 256 #
44.face $73 $74 $75 $2 $-1 $76 forward single #
45.loop $-1 $-1 $36 $25 #
46.plane-surface $77 -35.894024639034569 -68.554886883554843 0 0 1 0
   0 0 1 0 I I I I #
47.coedge $-1 $32 $68 $78 $79 1 $26 $-1 #
48.SURFACE_ID-Designer-attrib $-1 $-1 $-1 $27 0 0 #
49.coedge $-1 $78 $28 $30 $54 0 $16 $-1 #
50.coedge $-1 $28 $78 $80 $81 0 $16 $-1 #
51.coedge $-1 $82 $83 $28 $52 1 $84 $-1 #
52.edge $85 $86 $87 $51 $88 0 #
53.coedge $-1 $31 $30 $89 $90 0 $10 $-1 #
54.edge $91 $87 $56 $49 $92 0 #
55.color-adesk-attrib $-1 $-1 $-1 $33 256 #
56.vertex $-1 $33 $93 #
57.ellipse-curve $94 -45.894024639034569 -208.55488688355484 0 0 0 -
   1 3.5355339059327373 -3.5355339059327373 0 1 I I #
58.coedge $-1 $95 $96 $34 $59 1 $75 $-1 #
59.edge $97 $61 $66 $58 $98 0 #
60.color-adesk-attrib $-1 $-1 $-1 $35 256 #
61.vertex $-1 $99 $100 #
62.ellipse-curve $101 -40.894024639034569 -208.55488688355484 -5 0 -
   1 0 3.5355339059327373 0 3.5355339059327373 1 I I #
63.coedge $-1 $102 $36 $96 $103 0 $45 $-1 #
64.coedge $-1 $36 $104 $38 $69 0 $45 $-1 #
65.color-adesk-attrib $-1 $-1 $-1 $37 256 #
66.vertex $-1 $59 $105 #
67.ellipse-curve $106 -40.894024639034562 -68.554886883554843 -5 0 -
   1 0 3.5355339059327329 0 3.5355339059327431 1 I I #
68.coedge $-1 $47 $38 $107 $108 1 $26 $-1 #
69.edge $109 $110 $40 $64 $111 0 #
70.point $-1 -40.894024639034569 -68.554886883554872 0 #
71.point $-1 -40.894024639034569 -208.55488688355484 0 #
72.OWNER_TAG-Designer-attrib $-1 $-1 $-1 $42 #
73.color-adesk-attrib $-1 $-1 $-1 $44 256 #
74.face $112 $113 $114 $2 $-1 $115 forward single #
75.loop $-1 $-1 $58 $44 #
```

```
76.plane-surface $116 -35.894024639034569 -218.55488688355484 0 1 0
   0 0 0 -1 0 I I I I #
77.SURFACE_ID-Designer-attrib $-1 $-1 $-1 $46 65537 0 #
78.coedge $-1 $50 $49 $47 $79 0 $16 $-1 #
79.edge $117 $56 $118 $47 $119 0 #
80.coedge $-1 $107 $120 $50 $81 1 $121 $-1 #
81.edge $122 $118 $86 $80 $123 0 #
82.coedge $-1 $124 $51 $120 $125 0 $84 $-1 #
83.coedge $-1 $51 $124 $126 $127 1 $84 $-1 #
84.loop $-1 $-1 $51 $128 #
85.color-adesk-attrib $-1 $-1 $-1 $52 256 #
86.vertex $-1 $52 $129 #
87.vertex $-1 $90 $130 #
88.straight-curve $131 -148.3940246390346 -218.55488688355484 -5 1 0
   0 F -53 F 118.0000000000003 #
89.coedge $-1 $126 $132 $53 $90 1 $114 $-1 #
90.edge $133 $87 $61 $89 $134 0 #
91.color-adesk-attrib $-1 $-1 $-1 $54 256 #
92.ellipse-curve $135 -45.894024639034569 -213.55488688355484 -5 -1
   0 0 0 -3.5355339059327373 3.5355339059327373 1 I I #
93.point $-1 -45.894024639034569 -213.55488688355484 0 #
94.OWNER_TAG-Designer-attrib $-1 $-1 $-1 $57 #
95.coedge $-1 $136 $58 $132 $99 1 $75 $-1 #
96.coedge $-1 $58 $136 $63 $103 1 $75 $-1 #
97.color-adesk-attrib $-1 $-1 $-1 $59 256 #
98.straight-curve $137 -35.894024639034569 -181.05488688355484 -5 0
   1 0 F -43 F 128 #
99.edge $138 $139 $61 $95 $140 0 #
100.  point $-1 -35.894024639034569 -208.55488688355484 -5 #
101.  OWNER_TAG-Designer-attrib $-1 $-1 $-1 $62 #
102.  coedge $-1 $104 $63 $141 $142 0 $45 $-1 #
103.  edge $143 $66 $144 $63 $145 0 #
104.  coedge $-1 $64 $102 $146 $147 1 $45 $-1 #
105.  point $-1 -35.894024639034569 -68.554886883554843 -5 #
106.  OWNER_TAG-Designer-attrib $-1 $-1 $-1 $67 #
107.  coedge $-1 $146 $80 $68 $108 0 $121 $-1 #
108.  edge $148 $118 $110 $107 $149 0 #
109.  color-adesk-attrib $-1 $-1 $-1 $69 256 #
110.  vertex $-1 $69 $150 #
111.  straight-curve $151 70.276324866906805 -68.554886883554872 0 1
   0 0 I I #
112.  color-adesk-attrib $-1 $-1 $-1 $74 256 #
113.  face $152 $128 $121 $2 $-1 $153 forward single #
114.  loop $-1 $-1 $89 $74 #
115.  cone-surface $154 -45.894024639034569 -208.55488688355484 0 0
   0 -1 7.0710678118654746 -7.0710678118654746 0 1 I I 0 1 0 I I I I
   #
116.  SURFACE_ID-Designer-attrib $-1 $-1 $-1 $76 65539 0 #
117.  color-adesk-attrib $-1 $-1 $-1 $79 256 #
118.  vertex $-1 $81 $155 #
119.  straight-curve $156 -148.3940246390346 -213.55488688355484 0 -
   1 0 0 F -118.0000000000003 F 53 #
120.  coedge $-1 $80 $157 $82 $125 1 $121 $-1 #
121.  loop $-1 $-1 $80 $113 #
122.  color-adesk-attrib $-1 $-1 $-1 $81 256 #
123.  ellipse-curve $158 -185.8940246390346 -213.55488688355484 -5 1
   0 0 0 -3.5355339059327373 3.5355339059327373 1 I I #
124.  coedge $-1 $83 $82 $159 $160 0 $84 $-1 #
```

```
125.  edge $161 $86 $162 $82 $163 0 #
126.  coedge $-1 $164 $89 $83 $127 0 $114 $-1 #
127.  edge $165 $87 $166 $83 $167 0 #
128.  face $168 $169 $84 $2 $-1 $170 forward single #
129.  point $-1 -185.8940246390346 -218.55488688355484 -5 #
130.  point $-1 -45.894024639034569 -218.55488688355484 -5 #
131.  OWNER_TAG-Designer-attrib $-1 $-1 $-1 $88 #
132.  coedge $-1 $89 $164 $95 $99 0 $114 $-1 #
133.  color-adesk-attrib $-1 $-1 $-1 $90 256 #
134.  ellipse-curve $171 -45.894024639034569 -208.55488688355484 -5
   0 0 1 7.0710678118654746 -7.0710678118654746 0 1 I I #
135.  OWNER_TAG-Designer-attrib $-1 $-1 $-1 $92 #
136.  coedge $-1 $96 $95 $172 $173 0 $75 $-1 #
137.  OWNER_TAG-Designer-attrib $-1 $-1 $-1 $98 #
138.  color-adesk-attrib $-1 $-1 $-1 $99 256 #
139.  vertex $-1 $99 $174 #
140.  straight-curve $175 -35.894024639034569 -208.55488688355484 0
   0 0 1 F -131 F 31 #
141.  coedge $-1 $172 $176 $102 $142 1 $177 $-1 #
142.  edge $178 $144 $179 $102 $180 0 #
143.  color-adesk-attrib $-1 $-1 $-1 $103 256 #
144.  vertex $-1 $103 $181 #
145.  straight-curve $182 -35.894024639034569 -68.554886883554843 0
   0 0 -1 I I #
146.  coedge $-1 $157 $107 $104 $147 0 $121 $-1 #
147.  edge $183 $110 $179 $146 $184 0 #
148.  color-adesk-attrib $-1 $-1 $-1 $108 256 #
149.  straight-curve $185 -185.8940246390346 -119.76532576483297 0 0
   1 0 I I #
150.  point $-1 -185.8940246390346 -68.554886883554872 0 #
151.  OWNER_TAG-Designer-attrib $-1 $-1 $-1 $111 #
152.  color-adesk-attrib $-1 $-1 $-1 $113 256 #
153.  plane-surface $186 -185.8940246390346 -68.554886883554872 0 -1
   0 0 0 0 1 0 I I I I #
154.  SURFACE_ID-Designer-attrib $-1 $-1 $-1 $115 1 0 #
155.  point $-1 -185.8940246390346 -213.55488688355484 0 #
156.  OWNER_TAG-Designer-attrib $-1 $-1 $-1 $119 #
157.  coedge $-1 $120 $146 $176 $187 0 $121 $-1 #
158.  OWNER_TAG-Designer-attrib $-1 $-1 $-1 $123 #
159.  coedge $-1 $176 $188 $124 $160 1 $177 $-1 #
160.  edge $189 $162 $166 $124 $190 0 #
161.  color-adesk-attrib $-1 $-1 $-1 $125 256 #
162.  vertex $-1 $125 $191 #
163.  straight-curve $192 -185.8940246390346 -218.55488688355484 0 0
   0 -1 I I #
164.  coedge $-1 $132 $126 $188 $193 0 $114 $-1 #
165.  color-adesk-attrib $-1 $-1 $-1 $127 256 #
166.  vertex $-1 $160 $194 #
167.  straight-curve $195 -45.894024639034569 -218.55488688355484 0
   0 0 -1 F -31 F 131 #
168.  color-adesk-attrib $-1 $-1 $-1 $128 256 #
169.  face $196 $-1 $177 $2 $-1 $197 reversed single #
170.  plane-surface $198 -185.8940246390346 -218.55488688355484 0 0
   -1 0 0 0 -1 0 I I I I #
171.  OWNER_TAG-Designer-attrib $-1 $-1 $-1 $134 #
172.  coedge $-1 $188 $141 $136 $173 1 $177 $-1 #
173.  edge $199 $139 $144 $136 $200 0 #
174.  point $-1 -35.894024639034569 -208.55488688355484 -100 #
```

```
175. OWNER_TAG-Designer-attrib $-1 $-1 $-1 $140 #
176. coedge $-1 $141 $159 $157 $187 1 $177 $-1 #
177. loop $-1 $-1 $188 $169 #
178. color-adesk-attrib $-1 $-1 $-1 $142 256 #
179. vertex $-1 $147 $201 #
180. straight-curve $202 70.276324866906805 -68.554886883554872 -
   100 -1 0 0 I I #
181. point $-1 -35.894024639034569 -68.554886883554843 -100 #
182. OWNER_TAG-Designer-attrib $-1 $-1 $-1 $145 #
183. color-adesk-attrib $-1 $-1 $-1 $147 256 #
184. straight-curve $203 -185.8940246390346 -68.554886883554872 0 0
   0 -1 I I #
185. OWNER_TAG-Designer-attrib $-1 $-1 $-1 $149 #
186. SURFACE_ID-Designer-attrib $-1 $-1 $-1 $153 65543 0 #
187. edge $204 $179 $162 $157 $205 0 #
188. coedge $-1 $159 $172 $164 $193 1 $177 $-1 #
189. color-adesk-attrib $-1 $-1 $-1 $160 256 #
190. straight-curve $206 70.276324866906833 -218.55488688355484 -
   100 1 0 0 I I #
191. point $-1 -185.8940246390346 -218.55488688355484 -100 #
192. OWNER_TAG-Designer-attrib $-1 $-1 $-1 $163 #
193. edge $207 $166 $139 $188 $208 0 #
194. point $-1 -45.894024639034569 -218.55488688355484 -100 #
195. OWNER_TAG-Designer-attrib $-1 $-1 $-1 $167 #
196. color-adesk-attrib $-1 $-1 $-1 $169 256 #
197. plane-surface $209 -185.8940246390346 -68.554886883554872 -100
   0 0 1 1 0 0 0 I I I I #
198. SURFACE_ID-Designer-attrib $-1 $-1 $-1 $170 65541 0 #
199. color-adesk-attrib $-1 $-1 $-1 $173 256 #
200. straight-curve $210 -35.894024639034569 -119.76532576483297 -
   100 0 1 0 I I #
201. point $-1 -185.8940246390346 -68.554886883554872 -100 #
202. OWNER_TAG-Designer-attrib $-1 $-1 $-1 $180 #
203. OWNER_TAG-Designer-attrib $-1 $-1 $-1 $184 #
204. color-adesk-attrib $-1 $-1 $-1 $187 256 #
205. straight-curve $211 -185.8940246390346 -119.76532576483297 -
   100 0 -1 0 I I #
206. OWNER_TAG-Designer-attrib $-1 $-1 $-1 $190 #
207. color-adesk-attrib $-1 $-1 $-1 $193 256 #
208. ellipse-curve $212 -45.894024639034569 -208.55488688355484 -
   100 0 0 1 7.0710678118654746 -7.0710678118654746 0 1 I I #
209. SURFACE_ID-Designer-attrib $-1 $-1 $-1 $197 1 0 #
210. OWNER_TAG-Designer-attrib $-1 $-1 $-1 $200 #
211. OWNER_TAG-Designer-attrib $-1 $-1 $-1 $205 #
212. OWNER_TAG-Designer-attrib $-1 $-1 $-1 $208 #
```

Appendix 4. Text report of the evaluation of Real1.sat sample part.

DATA FILE TO STORE FEATURE EVALUATION RESULTS

FEATURE IDENTIFICATION RESULTS

Feature Matrix

Face	Pock	Step	Boss	Prot	Slot	Thol	Cpck	Bstp
9	0	0	0	0	0	1	0	0
11	0	0	0	0	0	1	0	0
16	0	0	0	0	0	1	0	0
25	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0
59	0	0	0	0	0	0	0	0
89	0	0	0	0	0	0	0	0
129	0	0	0	0	0	0	0	0
188	0	0	0	0	0	0	0	0
278	0	0	0	0	0	0	0	0
417	0	0	0	0	0	0	0	0
630	0	0	0	0	0	0	0	0
932	0	0	0	0	0	0	0	0
560	0	0	0	0	0	0	0	0
840	0	0	0	0	0	0	0	0
1190	0	0	0	0	0	0	0	0
1393	0	0	0	0	0	0	0	0
1824	0	0	0	0	0	0	0	0
1494	0	0	0	0	0	0	0	0
1937	0	0	0	0	0	0	0	0
2424	0	0	0	0	0	0	0	0
2311	0	0	0	0	0	0	0	0
2241	0	0	0	0	0	0	0	0
647	0	0	0	0	0	0	0	0
305	0	0	0	0	0	0	0	0
460	0	0	0	0	0	0	0	0
164	0	0	0	1	0	0	0	0
236	0	0	0	0	0	0	0	0
341	0	0	0	0	0	0	0	0
118	0	0	0	0	0	0	0	0
173	0	0	0	0	0	0	0	0
251	0	0	0	0	0	0	0	0
373	0	0	0	0	0	0	0	0
569	0	0	0	0	0	0	0	0
848	0	0	0	0	0	0	0	0
82	0	0	0	0	0	0	0	0
124	0	0	0	0	0	0	0	0
113	0	0	0	0	0	0	0	0
169	0	0	0	0	0	0	0	0
240	0	0	0	0	0	0	0	0
348	0	0	0	0	0	0	0	0
522	0	0	0	0	0	0	0	0
767	0	0	0	0	0	0	0	0
1095	0	0	0	0	0	0	0	0
1504	0	0	0	0	0	0	0	0
1958	0	0	0	0	0	0	0	0
2439	0	0	0	0	0	0	0	0
2229	0	0	0	0	0	0	0	0
2723	0	0	0	0	0	0	0	0
2707	0	0	0	0	0	0	0	0
1729	0	0	0	0	0	0	0	0

901	0	0	0	0	0	0	0	0
1285	0	0	0	0	0	0	0	0
1736	0	0	0	0	0	0	0	0
1271	0	0	0	0	0	0	0	0
1720	0	0	0	0	0	0	0	0
2204	0	0	0	0	0	0	0	0
2660	0	0	0	0	0	0	0	0
3140	0	0	0	0	0	0	0	0
3581	0	0	0	0	0	0	0	0
3983	0	0	0	0	0	0	0	0
4326	0	0	0	0	0	0	0	0
4578	0	0	0	0	0	0	0	0
4312	0	0	0	0	0	0	0	0
3122	0	0	0	0	0	0	0	0
2175	0	0	0	0	0	0	0	0
2673	0	0	0	0	0	0	0	0
3155	0	0	0	0	0	0	0	0
3607	0	0	0	0	0	0	0	0
4003	0	0	0	0	0	0	0	0
4346	0	0	0	0	0	0	0	0
3882	0	0	0	0	0	0	0	0
4258	0	0	0	0	0	0	0	0
3455	0	0	0	0	0	0	0	0
3871	0	0	0	0	0	0	0	0
4243	0	0	0	0	0	0	0	0
4443	0	0	0	0	0	0	0	0
3789	0	0	0	0	0	0	0	0
4168	0	0	0	1	0	0	0	0
3384	0	0	0	0	0	0	0	0
3797	0	1	0	0	0	0	0	0
4175	0	0	0	0	0	0	0	0
3404	0	0	0	0	0	0	0	0
3811	0	0	0	0	0	0	0	0
3162	0	0	0	0	0	0	0	0
1747	0	0	0	0	0	0	0	0
1705	0	0	0	0	0	0	0	0
2187	0	0	0	0	0	0	0	0
2033	0	0	0	0	0	0	0	0
2530	0	0	0	0	0	0	0	0
3009	0	0	0	0	0	0	0	0
3469	0	0	0	0	0	0	0	0
3888	0	0	0	0	0	0	0	0
4263	0	0	0	0	0	0	0	0
4540	0	0	0	0	0	0	0	0
4366	0	0	0	0	1	0	0	0
3676	0	0	0	0	0	0	0	0
4063	0	0	0	0	0	0	0	0
3835	0	0	0	0	0	0	0	0
3428	0	0	0	0	0	0	0	0
2986	0	0	0	0	0	0	0	0
2509	0	0	0	0	0	0	0	0
1903	0	0	0	0	0	0	0	0
1440	0	0	0	0	0	0	0	0
1898	0	0	0	0	0	0	0	0
2385	0	0	0	0	0	0	0	0
2864	0	0	0	0	0	0	0	0
3314	0	0	0	0	0	0	0	0
3557	0	0	0	0	0	0	0	0
3943	0	0	0	0	0	0	0	0
3903	0	0	0	0	0	0	0	0
3302	0	0	0	0	0	0	0	0
2378	0	0	0	0	0	0	0	0
1880	0	0	0	0	0	0	0	0
2363	0	0	0	0	0	0	0	0

2839	0	0	0	0	0	0	0	0
3210	0	0	0	0	0	0	0	0
2748	0	0	0	0	0	0	0	0
2834	0	0	0	0	0	0	0	0
2348	0	0	0	0	0	0	0	0
2815	0	0	0	0	0	0	0	0
2398	0	0	0	0	0	0	0	0
1919	0	0	0	0	0	0	0	0
1464	0	0	0	0	0	0	0	0
1250	0	0	0	0	0	0	0	0
1686	0	0	0	0	0	0	0	0
2156	0	0	0	0	0	0	0	0
2638	0	0	0	0	0	0	0	0
3101	0	0	0	0	0	0	0	0
3541	0	0	0	0	0	0	0	0
2588	0	0	0	0	0	0	0	0
3058	0	0	0	0	0	0	0	0
3509	0	0	0	0	0	0	0	0
3914	0	0	0	0	0	0	0	0
2114	0	0	0	0	0	0	0	0
1651	0	0	0	0	0	0	0	0
1231	0	0	0	0	0	0	0	0
876	0	0	0	0	0	0	0	0
1246	0	0	0	0	0	0	0	0
1679	0	0	0	0	0	0	0	0
1365	0	0	0	0	0	0	0	0
1590	0	0	0	0	0	0	0	0
1170	0	0	0	0	0	0	0	0
823	0	0	0	0	0	0	0	0
1182	0	0	0	0	0	0	0	0
1614	0	0	0	0	0	0	0	0
1814	0	0	0	0	0	0	0	1
1360	0	0	0	0	0	0	0	0
689	0	0	0	0	0	0	0	0
968	0	0	0	0	0	0	0	0
1355	0	0	0	0	0	0	0	0
1799	0	0	0	0	0	0	0	0
2276	0	0	0	0	0	0	0	0
2762	0	0	0	0	0	0	0	0
3232	0	0	1	0	0	0	0	0
3665	0	0	0	0	0	0	0	0
3264	0	0	0	0	0	0	0	0
3692	0	0	0	0	0	0	0	0
1028	0	0	0	0	0	0	0	0
1032	0	0	0	0	0	0	0	0
1419	0	0	0	0	0	0	0	0
1859	0	0	0	0	0	0	0	0
1210	0	0	0	0	0	0	0	0
1632	0	0	0	0	0	0	0	0
1944	0	0	0	0	0	0	0	0
610	0	0	0	0	0	0	0	0

Potential Feature Matrix
Confidence Factors

```
 Face  Pock  Step  Boss  Prot  Slot  Thol  Cpck  Bstp

    91.2e-111.4e-072.5e-06 2e-154.3e-13  0.990.000138.9e-13

   111.2e-111.5e-07 6e-072.3e-151.1e-14  0.990.000237.1e-13

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  6101.2e-114.2e-08 0.0080.00244.1e-074.8e-05  0.013.7e-13
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FEATURE IDENTIFICATION REPORT

Feature corresponding to FACE 9 is a T_HOLE

Feature corresponding to FACE 11 is a T_HOLE

Feature corresponding to FACE 16 is a T_HOLE

Feature corresponding to FACE 164 is a PROTRUSION

Feature corresponding to FACE 4168 is a PROTRUSION
Feature corresponding to FACE 3797 is a STEP
Feature corresponding to FACE 4366 is a SLOT
Feature corresponding to FACE 1814 is a B_STEP
Feature corresponding to FACE 3232 is a BOSS

FEATURE EVALUATION REPORT

T_Hole Feature 9 requires special moulding process.
T_Hole Feature 9 can be moulded in the part
T_Hole Feature 9 has a cylinder angle that need to be aligned to Z axis

T_Hole Feature 11 can be moulded in the part

T_Hole Feature 11 has a Draft-Angle of Face 164 OK.

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T_Hole Feature 16 can be moulded in the part

T_Hole Feature 16  has a Draft-Angle of Face 164 OK.

Protrusion Feature 164  has a Top-fillet of Face 1824 too small

Protrusion Feature 164  has a Top-fillet of Face 1393 too small

Protrusion Feature 164  has a Top-fillet of Face 932 too small
Protrusion Feature 164  has a Top-fillet of Face 560 too small
Protrusion Feature 164  has a Draft-Angle of Face 1944 too small
Protrusion Feature 164  has a Draft-Angle of Face 1937 too small
Protrusion Feature 164  has a Draft-Angle of Face 2311 OK
Protrusion Feature 164  has a Draft-Angle of Face 118 too small
 Protrusion Feature 164 Bottom-Fillet: Fillet of Face 1944  does not exist
 Protrusion Feature 164 Bottom-Fillet: Fillet of Face 1937  does not exist
Protrusion Feature 164  has a Bottom-Fillet of Face 3676 too small
 Protrusion Feature 164 Bottom-Fillet: Fillet of Face 118  does not exist


Protrusion Feature 4168  has a Top-fillet of Face 4258 too small

Protrusion Feature 4168  has a Top-fillet of Face 4003 too small
Protrusion Feature 4168  has a Top-fillet of Face 3607 too small
Protrusion Feature 4168  has a Top-fillet of Face 3455 too small
Protrusion Feature 4168  has a Draft-Angle of Face 4243 OK
Protrusion Feature 4168  has a Draft-Angle of Face 4175 OK
Protrusion Feature 4168  has a Draft-Angle of Face 1937 too small
Protrusion Feature 4168  has a Draft-Angle of Face 118 too small
Protrusion Feature 4168  has a Bottom-Fillet of Face 4540 too small
Protrusion Feature 4168  has a Bottom-Fillet of Face 3797 too small
 Protrusion Feature 4168 Bottom-Fillet: Fillet of Face 1937  does not exist
 Protrusion Feature 4168 Bottom-Fillet: Fillet of Face 118  does not exist


Step Feature 3797  has a Main-fillet too small
Step Feature 3797 has a Draft-Angle of Face 4175 too small
Step Feature 3797 has a Draft-Angle of Face 1958 OK.
Step Feature 3797 has an external fillet of Face4003 too small.
Step Feature 3797 has an external fillet of Face767 too small.


Slot Feature 4366  has a bottom-fillet of face 3888 too small.
Slot Feature 4366  has a bottom-fillet of face 3210 too small.
Slot Feature 4366  has a bottom-fillet of face 4540 too small.
Slot Feature 4366  has a bottom-fillet of face 3676 too small.
Slot Feature 4366  has a Draft-Angle of Face 1937 too small
Slot Feature 4366  has a Draft-Angle of Face 118 too small
Slot Feature 4366  has a Draft-Angle of Face 4243 OK
Slot Feature 4366  has a Draft-Angle of Face 2311 OK
 Slot Feature 4366 Top-Fillet: Fillet of Face 1937  does not exist
 Slot Feature 4366 Top-Fillet: Fillet of Face 118  does not exist
Slot Feature 4366  has a Top-Fillet of Face 4258 too small
Slot Feature 4366  has a Top-Fillet of Face 932 too small


Blind-Step Feature 1814  has a Main-fillet too small
Blind-Step Feature 1814  has a Draft-Angle of Face 1799 OK
Blind-Step Feature 1814  has a Draft-Angle of Face 689 too small
Blind-Step Feature 1814  has a Lateral Draft-Angle of Face 1419 too small.
Blind-Step Feature 1814  has a Lateral Draft-Angle of Face 305 too small.
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Boss Feature 3232 has a Top-Fillet of Face 2276 too small.

Boss Feature 3232 has a D/H ratio of Face 2762 too small.

Boss Feature 3232 has a Draft-Angle of Face 2762 OK

Boss Feature 3232 has a Bottom-Fillet of Face 1028 too small

MODEL'S GEOMETRICAL AND TOPOLOGICAL DATA

FACE	TYPE	ZANGLE	Direc	cos	minR	MinRi	FGS	FVS	FS
9	1	85	1	1	0	0	-2	-1	-3
11	1	0	1	1	0	0	-2	-1	-3
16	1	0	1	1	0	0	-2	-1	-3
25	4	0	0	0	0	0	0	-0.25	-0.25
38	1	90	0	1	0	0	2	0.875	2.88
59	1	90	0	1	0	0	2	-0.25	1.75
89	2	0	0	0	5	0	2	2	4
129	4	0	0	0	0	0	0	-0.25	-0.25
188	1	90	0	1	0	0	2	2	4
278	1	90	0	1	0	0	2	0.875	2.88
417	2	0	0	0	5	0	2	2	4
630	2	0	0	0	5	0	2	2	4
932	1	90	0	1	0	0	2	2	4
560	1	90	0	1	0	0	2	2	4
840	2	0	0	0	5	0	2	2	4
1190	2	0	0	0	5	0	2	2	4
1393	1	90	0	1	0	0	2	2	4
1824	1	90	0	1	0	0	2	2	4
1494	2	0	0	0	5	0	2	2	4
1937	5	85	0	0	0	0	0	1.23	1.23
2424	1	174	0	1	0	0	2	1.12	3.12
2311	5	87	1	0	0	0	0	1	1
2241	1	5.82	0	1	0	0	2	0.875	2.88
647	1	175	0	1	0	0	2	0.875	2.88
305	5	87	1	0	0	0	0	0	0
460	1	176	0	-1	0	0	-2	-1	-3
164	5	0	1	0	0	0	0	0.538	0.538
236	1	7.05	0	1	0	0	2	1.75	3.75
341	1	7.05	0	1	0	0	2	1.75	3.75
118	5	85	0	0	0	0	0	0.75	0.75
173	1	7.05	0	-1	0	0	-2	-1.25	-3.25
251	2	0	0	0	-5	0	-2	-2	-4
373	1	90	0	-1	0	0	-2	-2	-4
569	2	0	0	0	-5	0	-2	-2	-4
848	1	7.05	0	-1	0	0	-2	-1.25	-3.25
82	5	95	1	0	0	0	0	-1.05	-1.05
124	1	90	0	-1	0	0	-2	-2	-4
113	5	180	0	0	0	0	0	-1.15	-1.15
169	1	90	0	-1	0	0	-2	-2	-4
240	5	95	1	0	0	0	0	-1.08	-1.08
348	1	7.05	0	1	0	0	2	1.75	3.75
522	2	0	0	0	5	0	2	2	4
767	1	90	0	1	0	0	2	2	4
1095	2	0	0	0	5	0	2	2	4
1504	1	7.05	0	1	0	0	2	1.75	3.75
1958	5	0	1	0	0	0	0	1	1
2439	1	90	0	1	0	0	2	1.12	3.12
2229	1	7.05	0	-1	0	0	-2	-1.25	-3.25
2723	2	0	0	0	-5	0	-2	-2	-4
2707	1	90	0	-1	0	0	-2	-2	-4
1729	2	0	0	0	-5	0	-2	-2	-4
901	1	7.05	0	-1	0	0	-2	-1.25	-3.25
1285	1	90	0	-1	0	0	-2	-1.12	-3.12
1736	5	180	1	0	0	0	0	-1	-1
1271	1	90	0	-1	0	0	-2	-1.12	-3.12
1720	2	0	0	0	-5	0	-2	-2	-4
2204	1	90	0	-1	0	0	-2	-2	-4
2660	1	90	0	-1	0	0	-2	-2	-4
3140	2	0	0	0	-5	0	-2	-2	-4
3581	2	0	0	0	-5	0	-2	-2	-4

3983	1	90	0	-1	0	0	-2	-2	-4
4326	1	90	0	-1	0	0	-2	-2	-4
4578	2	0	0	0	-5	0	-2	-2	-4
4312	5	93	0	0	0	0	0	-1	-1
3122	1	5.82	0	-1	0	0	-2	-1.12	-3.12
2175	1	174	0	-1	0	0	-2	-1.12	-3.12
2673	5	180	0	0	0	0	0	-2	-2
3155	2	0	0	0	5	0	2	2	4
3607	1	90	0	1	0	0	2	2	4
4003	1	90	0	1	0	0	2	2	4
4346	2	0	0	0	5	0	2	2	4
3882	2	0	0	0	5	0	2	2	4
4258	1	90	0	1	0	0	2	2	4
3455	1	90	0	1	0	0	2	2	4
3871	2	0	0	0	5	0	2	2	4
4243	5	87	1	0	0	0	0	1	1
4443	1	5.82	0	1	0	0	2	1.12	3.12
3789	1	174	0	1	0	0	2	1.12	3.12
4168	5	0	1	0	0	0	0	2	2
3384	4	0	0	0	0	0	0	0.25	0.25
3797	1	90	0	-1	0	0	-2	0	-2
4175	5	87	1	0	0	0	0	1	1
3404	4	0	0	0	0	0	0	-0.25	-0.25
3811	1	5.82	0	-1	0	0	-2	-1.12	-3.12
3162	1	90	0	1	0	0	2	0	2
1747	5	95	1	0	0	0	0	-1.25	-1.25
1705	4	0	0	0	0	0	0	-0.25	-0.25
2187	5	93	0	0	0	0	0	-1	-1
2033	1	90	0	1	0	0	2	1.12	3.12
2530	4	0	0	0	0	0	0	0.25	0.25
3009	1	5.82	0	1	0	0	2	1.12	3.12
3469	4	0	0	0	0	0	0	0.25	0.25
3888	1	90	0	1	0	0	2	0.25	2.25
4263	4	0	0	0	0	0	0	0.25	0.25
4540	1	90	0	-1	0	0	-2	0	-2
4366	5	0	1	0	0	0	0	0	0
3676	1	90	0	-1	0	0	-2	0	-2
4063	1	174	0	-1	0	0	-2	-1.12	-3.12
3835	4	0	0	0	0	0	0	-0.25	-0.25
3428	1	90	0	-1	0	0	-2	-0.25	-2.25
2986	4	0	0	0	0	0	0	-0.25	-0.25
2509	1	5.82	0	-1	0	0	-2	-1.12	-3.12
1903	2	0	0	0	-5	0	-2	-2	-4
1440	1	90	0	-1	0	0	-2	-2	-4
1898	5	93	0	0	0	0	0	-1	-1
2385	1	90	0	1	0	0	2	0	2
2864	5	180	1	0	0	0	0	0	0
3314	1	90	0	1	0	0	2	0	2
3557	4	0	0	0	0	0	0	-0.25	-0.25
3943	1	90	0	-1	0	0	-2	-0.25	-2.25
3903	4	0	0	0	0	0	0	-0.25	-0.25
3302	1	174	0	-1	0	0	-2	-1.12	-3.12
2378	2	0	0	0	-5	0	-2	-2	-4
1880	1	90	0	-1	0	0	-2	-2	-4
2363	1	174	0	1	0	0	2	1.12	3.12
2839	4	0	0	0	0	0	0	0.25	0.25
3210	1	90	0	1	0	0	2	0	2
2748	4	0	0	0	0	0	0	-0.25	-0.25
2834	2	0	0	0	-5	0	-2	-2	-4
2348	1	90	0	-1	0	0	-2	-1.12	-3.12
2815	4	0	0	0	0	0	0	-0.25	-0.25
2398	1	90	0	-1	0	0	-2	-0.25	-2.25
1919	4	0	0	0	0	0	0	-0.25	-0.25
1464	1	90	0	-1	0	0	-2	-1.12	-3.12
1250	2	0	0	0	-5	0	-2	-2	-4
1686	5	93	0	0	0	0	0	0	0
2156	1	176	0	1	0	0	2	1	3
2638	5	93	0	0	0	0	0	1	1
3101	1	176	0	1	0	0	2	1	3
3541	5	93	0	0	0	0	0	0	0
2588	1	5.44	0	-1	0	0	-2	-1.12	-3.12
3058	2	0	0	0	5	0	2	2	4
3509	1	90	0	1	0	0	2	2	4
3914	2	0	0	0	5	0	2	2	4
2114	4	0	0	0	0	0	0	-0.25	-0.25
1651	1	90	0	-1	0	0	-2	-0.25	-2.25
1231	4	0	0	0	0	0	0	-0.25	-0.25

876	1	175	0	-1	0	0	-2	-1.12	-3.12
1246	1	90	0	1	0	0	2	1	3
1679	1	90	0	1	0	0	2	1	3
1365	4	0	0	0	0	0	0	-0.25	-0.25
1590	1	90	0	1	0	0	2	-0.25	1.75
1170	4	0	-0	0	0	0	0	-0.25	-0.25
823	1	5.44	0	1	0	0	2	0.875	2.88
1182	1	176	0	-1	0	0	-2	-1	-3
1614	2	0	0	0	-5	0	-2	-2	-4
1814	1	90	0	-1	0	0	-2	-2	-4
1360	2	0	0	0	-5	0	-2	-2	-4
689	5	87	1	0	0	0	0	-1	-1
968	1	90	0	-1	0	0	-2	-1	-3
1355	1	90	0	-1	0	0	-2	-1	-3
1799	5	0	0	0	0	0	0	-1	-1
2276	3	0	0	0	0	5	2	1	3
2762	1	0	0	0.996	0	0	2	0	2
3232	5	0	0	0	0	0	0	1	1
3665	3	0	0	0	0	-5	-2	-1	-3
3264	1	180	1	0.996	0	0	-2	0	-2
3692	5	180	0	0	0	0	0	-1	-1
1028	3	0	0	0	0	-5	-2	-1	-3
1032	3	0	0	0	0	5	2	1	3
1419	5	87	1	0	0	0	0	0	0
1859	5	180	1	0	0	0	0	1	1
1210	5	95	1	0	0	0	0	-1.25	-1.25
1632	5	85	0	0	0	0	0	1.75	1.75
1944	5	85	0	0	0	0	0	1.75	1.75
610	5	180	1	0	0	0	0	0.5	0.5

fst	scd	thr	CD1	Z1	fst2	scd2	thr2	CD2	Z2	CAng
0	-1.31	-14.9	15	29.5	0	-1.31	-14.9	15	29.9	0
-10	0	0	10	95	-10	0	0	10	100	0
-10	0	0	10	95	-10	0	0	10	100	0
0	0	0	0	0	0	0	0	0	0	0
-3.39	-0.598	3.63	5	95	-3.39	-0.598	3.63	5	95	0
0	-3.44	3.63	5	95	0	-3.44	3.63	5	95	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	-3.38	3.69	5	95	0	-3.38	3.69	5	95	0
3.39	-0.598	3.63	5	95	3.39	-0.598	3.63	5	95	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
3.44	0	3.63	5	95	3.44	0	3.63	5	95	0
-1.93e-14	-3.38	3.69	5	95	0	-3.38	3.69	5	95	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	3.38	3.69	5	95	0	3.38	3.69	5	95	0
-3.38	0	3.69	5	95	-3.38	0	3.69	5	95	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
3.52	3.51	0.492	5	95	3.52	3.51	0.492	5	74.5	0
0	0	0	0	0	0	0	0	0	0	0
3.52	-3.51	0.492	5	95	3.52	-3.51	0.492	5	74.5	0
-3.2	-3.81	0.455	5	95	-3.2	-3.81	0.455	5	74.5	0
0	0	0	0	0	0	0	0	0	0	0
3.24	3.86	0.341	5.05	95	3.21	3.82	-0.341	5	75	-89.9
0	0	0	0	0	0	0	0	0	0	0
-3.51	3.51	0.614	5	95	-3.56	3.56	0	5.04	0	90
-3.51	-3.51	0.614	5	95	-3.56	-3.56	0	5.04	0	90
0	0	0	0	0	0	0	0	0	0	0
-3.51	-3.51	0.614	5	90	-3.56	-3.56	0	5.04	0	90
0	0	0	0	0	0	0	0	0	0	0
-3.38	0	3.69	5	90	-3.38	0	3.69	5	90	0
0	0	0	0	0	0	0	0	0	0	0
-3.56	3.56	0	5.04	0	-3.51	3.51	0.614	5	90	90
0	0	0	0	0	0	0	0	0	0	0
0	-3.38	3.69	5	90	0	-3.38	3.69	5	90	0
0	0	0	0	0	0	0	0	0	0	0
0	3.38	3.69	5	90	0	3.38	3.69	5	90	0
0	0	0	0	0	0	0	0	0	0	0
3.51	3.51	0.614	5	70	3.56	3.56	0	5.04	0	90
0	0	0	0	0	0	0	0	0	0	0
3.38	9.64e-15	3.69	5	70	3.38	0	3.69	5	70	0
0	0	0	0	0	0	0	0	0	0	0
3.56	-3.56	0	5.04	0	3.51	-3.51	0.614	5	70	90

```
      0      0      0      0      0      0      0      0      0      0      0
      0   3.38   3.69      5     70-7.71e-14   3.38   3.69      5     70      0
   3.51   3.51  0.614      5     65   3.56   3.56      0   5.04      0     90
      0      0      0      0      0      0      0      0      0      0      0
   3.38-1.2e-14   3.69      5     65   3.38      0   3.69      5     65      0
      0      0      0      0      0      0      0      0      0      0      0
   3.56  -3.56      0   5.04      0   3.51  -3.51  0.614      5     65     90
      0   3.38   3.69      5     65      0   3.38   3.69      5     65      0
      0      0      0      0      0      0      0      0      0      0      0
      0  -3.38   3.69      5     65      0  -3.38   3.69      5     65      0
      0      0      0      0      0      0      0      0      0      0      0
   3.44      0   3.63      5     90   3.44      0   3.63      5     90      0
7.71e-14  -3.38   3.69      5     90      0  -3.38   3.69      5     90      0
      0      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0      0
      0   3.38   3.69      5     90      0   3.38   3.69      5     90      0
  -3.44      0   3.63      5     90  -3.44      0   3.63      5     90      0
      0      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0      0
  -3.52  -3.51  0.492      5     90  -3.52  -3.51  0.492      5   69.5      0
   3.52  -3.51  0.492      5     90   3.52  -3.51  0.492      5   74.5      0
      0      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0      0
      0   3.38   3.69      5     95      0   3.38   3.69      5     95      0
   3.444.9e-15   3.63      5     95   3.44      0   3.63      5     95      0
      0      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0      0
  -3.44      0   3.63      5     95  -3.44      0   3.63      5     95      0
      0  -3.38   3.69      5     95      0  -3.38   3.69      5     95      0
      0      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0      0
  -3.52   3.51  0.492      5     95  -3.52   3.51  0.492      5   74.5      0
   3.52   3.51  0.492      5     95   3.52   3.51  0.492      5   79.5      0
      0      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0      0
-5.68e-14  0.875     -5   5.08     80-5.68e-14-0.875     -5   5.08     80      0
      0      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0      0
   3.52   3.51  0.492      5     90   3.52   3.51  0.492      5   74.5      0
-5.68e-14  0.875     -5   5.08     75-5.68e-14-0.875     -5   5.08     75      0
      0      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0      0
      0  -3.38   3.69      5     70-7.71e-14  -3.38   3.69      5     70      0
      0      0      0      0      0      0      0      0      0      0      0
   3.52  -3.51  0.492      5     95   3.52  -3.51  0.492      5   79.5      0
      0      0      0      0      0      0      0      0      0      0      0
      0   3.38   3.69      5     65      0   3.38   3.69      5     65      0
      0      0      0      0      0      0      0      0      0      0      0
      0  0.875     -5   5.08     75      0 -0.875     -5   5.08     75      0
      0      0      0      0      0      0      0      0      0      0      0
      0  0.875     -5   5.08     75      0 -0.875     -5   5.08     75      0
  -3.52   3.51  0.492      5     90  -3.52   3.51  0.492      5   69.5      0
      0      0      0      0      0      0      0      0      0      0      0
      0   3.38   3.69      5     60      0   3.38   3.69      5     60      0
      0      0      0      0      0      0      0      0      0      0      0
   3.52   3.51  0.492      5     90   3.52   3.51  0.492      5   69.5      0
      0      0      0      0      0      0      0      0      0      0      0
   3.44      0   3.63      5     90   3.44      0   3.63      5     90      0
      0      0      0      0      0      0      0      0      0      0      0
-5.68e-14  0.875     -5   5.08     70-5.68e-14-0.875     -5   5.08     70      0
      0      0      0      0      0      0      0      0      0      0      0
      0  0.875     -5   5.08     70      0 -0.875     -5   5.08     70      0
      0      0      0      0      0      0      0      0      0      0      0
      0  -3.38   3.69      5     60      0  -3.38   3.69      5     60      0
      0      0      0      0      0      0      0      0      0      0      0
   3.52  -3.51  0.492      5     90   3.52  -3.51  0.492      5   69.5      0
      0      0      0      0      0      0      0      0      0      0      0
      0  -3.38   3.69      5     90      0  -3.38   3.69      5     90      0
  -3.52  -3.51  0.492      5     95  -3.52  -3.51  0.492      5   74.5      0
      0      0      0      0      0      0      0      0      0      0      0
      0  -3.38   3.69      5     65      0  -3.38   3.69      5     65      0
      0      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0      0
  -3.39-0.598   3.63      5     90  -3.39-0.598   3.63      5     90      0
      0      0      0      0      0      0      0      0      0      0      0
      0  -3.44   3.63      5     90      0  -3.44   3.63      5     90      0
```

0	0	0	0	0	0	0	0	0	0	0
3.39	-0.598	3.63	5	90	3.39	-0.598	3.63	5	90	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
-3.24	3.86	0.341	5.05	90	-3.21	3.82	-0.341	5	70	-89.9
0	0	0	0	0	0	0	0	0	0	0
3.24	3.86	0.341	5.05	90	3.21	3.82	-0.341	5	70	-89.9
0	0	0	0	0	0	0	0	0	0	0
-3.2	-3.81	0.455	5	90	-3.2	-3.81	0.455	5	69.5	0
0	0	0	0	0	0	0	0	0	0	0
-3.92e-14	3.44	-3.63	5	70	0	3.44	-3.63	5	70	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
3.85e-14	-3.38	3.69	5	60	0	-3.38	3.69	5	60	0
0	0	0	0	0	0	0	0	0	0	0
3.2	-3.81	0.455	5	90	3.2	-3.81	0.455	5	69.5	0
3.39	0.598	-3.63	5	70	4.74	-1.17	-2.25	5.38	70	0
-3.39	0.598	-3.63	5	70	-4.74	-1.17	-2.25	5.38	70	0
0	0	0	0	0	0	0	0	0	0	0
3.85e-14	-3.38	3.69	5	65	0	-3.38	3.69	5	65	0
0	0	0	0	0	0	0	0	0	0	0
3.2	-3.81	0.455	5	95	3.2	-3.81	0.455	5	74.5	0
-3.24	3.86	0.341	5.05	95	-3.21	3.82	-0.341	5	75	-89.9
0	0	0	0	0	0	0	0	0	0	0
0	3.44	-3.63	5	75	0	3.44	-3.63	5	75	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
4.74	-1.17	-2.25	5.38	75	3.39	0.598	-3.63	5	75	0
-4.74	-1.17	-2.25	5.38	75	-3.39	0.598	-3.63	5	75	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
-32.1	0	0	32.1	105	-29.4	0	0	29.4	135	85
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
27.1	0	0	27.1	99.6	24.4	0	0	24.4	130	85
0	0	0	0	0	0	0	.0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0

Sharing-Edges faces

Face	Sharing-Edge faces												
9	118	82	0	0	0	0	0	0	0	0	0	0	
11	164	113	0	0	0	0	0	0	0	0	0	0	
16	164	113	0	0	0	0	0	0	0	0	0	0	
25	38	59	164	460	0	0	0	0	0	0	0	0	
38	89	164	305	25	0	0	0	0	0	0	0	0	
59	164	129	25	689	0	0	0	0	0	0	0	0	
89	188	647	38	0	0	0	0	0	0	0	0	0	
129	278	59	164	1182	0	0	0	0	0	0	0	0	
188	417	89	118	164	0	0	0	0	0	0	0	0	
278	630	164	1419	129	0	0	0	0	0	0	0	0	
417	932	188	2241	0	0	0	0	0	0	0	0	0	
630	560	823	278	0	0	0	0	0	0	0	0	0	
932	840	417	2311	164	0	0	0	0	0	0	0	0	
560	1190	630	118	164	0	0	0	0	0	0	0	0	
840	1393	932	2424	0	0	0	0	0	0	0	0	0	
1190	1824	560	341	0	0	0	0	0	0	0	0	0	
1393	1494	840	1937	164	0	0	0	0	0	0	0	0	
1824	1494	1190	1944	164	0	0	0	0	0	0	0	0	
1494	1824	1393	236	0	0	0	0	0	0	0	0	0	
1937	3607	1393	348	236	4443	3789	2439	2424	3888	610	4263	3469	
2424	840	1937	2311	3469	0	0	0	0	0	0	0	0	
2311	932	2424	2241	3676	0	0	0	0	0	0	0	0	
2241	417	2311	118	2748	0	0	0	0	0	0	0	0	
647	89	118	1365	305	0	0	0	0	0	0	0	0	
305	647	38	968	460	0	0	0	0	0	0	0	0	
460	689	1360	305	25	0	0	0	0	0	0	0	0	
164	1824	1393	932	560	188	278	38	59	129	25	1028	16	
236	1494	1944	1937	610	0	0	0	0	0	0	0	0	
341	1190	1944	118	610	0	0	0	0	0	0	0	0	
118	3455	560	188	1504	341	3009	2363	2033	2241	823	647	3210	

173	610	82	1210	251	0	0	0	0	0	0	0	0
251	173	373	124	0	0	0	0	0	0	0	0	0
373	113	1210	569	251	0	0	0	0	0	0	0	0
569	848	373	169	0	0	0	0	0	0	0	0	0
848	610	240	1210	569	0	0	0	0	0	0	0	0
82	610	3903	3557	2114	1705	1231	3943	1651	9	3302	3122	2588
124	82	113	1250	251	0	0	0	0	0	0	0	0
113	1032	2815	1919	2398	16	11	2348	1464	1880	1440	373	169
169	240	113	1903	569	0	0	0	0	0	0	0	0
240	610	3835	3404	2986	3428	4063	3811	2509	1285	2229	848	3983
348	522	1632	1937	610	0	0	0	0	0	0	0	0
522	767	348	2439	0	0	0	0	0	0	0	0	0
767	1095	522	1632	1958	0	0	0	0	0	0	0	0
1095	767	1504	2033	0	0	0	0	0	0	0	0	0
1504	1095	1632	118	610	0	0	0	0	0	0	0	0
1958	767	2439	2033	3797	0	0	0	0	0	0	0	0
2439	522	1937	1958	3384	0	0	0	0	0	0	0	0
2229	610	240	1747	2723	0	0	0	0	0	0	0	0
2723	1285	2229	2707	0	0	0	0	0	0	0	0	0
2707	1736	1747	2723	1729	0	0	0	0	0	0	0	0
1729	1271	901	2707	0	0	0	0	0	0	0	0	0
901	610	82	1747	1729	0	0	0	0	0	0	0	0
1285	3404	1736	240	2723	0	0	0	0	0	0	0	0
1736	3162	1285	1271	2707	0	0	0	0	0	0	0	0
1271	1705	1736	82	1729	0	0	0	0	0	0	0	0
1720	2175	2660	2204	0	0	0	0	0	0	0	0	0
2204	2187	2673	3140	1720	0	0	0	0	0	0	0	0
2660	82	2673	3581	1720	0	0	0	0	0	0	0	0
3140	3811	3983	2204	0	0	0	0	0	0	0	0	0
3581	3122	4326	2660	0	0	0	0	0	0	0	0	0
3983	240	2673	4578	3140	0	0	0	0	0	0	0	0
4326	4312	2673	4578	3581	0	0	0	0	0	0	0	0
4578	4063	4326	3983	0	0	0	0	0	0	0	0	0
4312	3314	4063	3122	4326	0	0	0	0	0	0	0	0
3122	3557	4312	82	3581	0	0	0	0	0	0	0	0
2175	1705	2187	82	1720	0	0	0	0	0	0	0	0
2673	4326	3983	2660	2204	0	0	0	0	0	0	0	0
3155	4003	3607	3789	0	0	0	0	0	0	0	0	0
3607	4346	3155	4168	1937	0	0	0	0	0	0	0	0
4003	3882	3155	4168	4175	0	0	0	0	0	0	0	0
4346	4258	3607	4443	0	0	0	0	0	0	0	0	0
3882	4003	3455	3009	0	0	0	0	0	0	0	0	0
4258	4346	3871	4168	4243	0	0	0	0	0	0	0	0
3455	3882	3871	4168	118	0	0	0	0	0	0	0	0
3871	4258	3455	2363	0	0	0	0	0	0	0	0	0
4243	4258	4443	2363	4540	0	0	0	0	0	0	0	0
4443	4346	1937	4243	4263	0	0	0	0	0	0	0	0
3789	3155	1937	4175	3384	0	0	0	0	0	0	0	0
4168	4258	4003	3607	3455	0	0	0	0	0	0	0	0
3384	3789	2439	1937	3797	0	0	0	0	0	0	0	0
3797	4175	1958	3384	2530	0	0	0	0	0	0	0	0
4175	4003	3789	3009	3797	0	0	0	0	0	0	0	0
3404	3162	240	3811	1285	0	0	0	0	0	0	0	0
3811	3404	2187	240	3140	0	0	0	0	0	0	0	0
3162	3404	1705	2187	1736	0	0	0	0	0	0	0	0
1747	610	2229	901	2707	0	0	0	0	0	0	0	0
1705	3162	82	2175	1271	0	0	0	0	0	0	0	0
2187	3162	3811	2175	2204	0	0	0	0	0	0	0	0
2033	1095	1958	118	2530	0	0	0	0	0	0	0	0
2530	3009	2033	118	3797	0	0	0	0	0	0	0	0
3009	3882	4175	118	2530	0	0	0	0	0	0	0	0
3469	2424	3888	1937	3676	0	0	0	0	0	0	0	0
3888	1937	4263	3469	4366	0	0	0	0	0	0	0	0
4263	4443	3888	1937	4540	0	0	0	0	0	0	0	0
4540	4243	4263	2839	4366	0	0	0	0	0	0	0	0
4366	3888	3210	4540	3676	0	0	0	0	0	0	0	0
3676	2311	3469	4366	2748	0	0	0	0	0	0	0	0
4063	3835	4312	240	4578	0	0	0	0	0	0	0	0
3835	3314	240	3428	4063	0	0	0	0	0	0	0	0
3428	3835	2986	2864	240	0	0	0	0	0	0	0	0
2986	2385	240	3428	2509	0	0	0	0	0	0	0	0
2509	2986	1898	240	1903	0	0	0	0	0	0	0	0
1903	2509	1440	169	0	0	0	0	0	0	0	0	0
1440	1898	113	2378	1903	0	0	0	0	0	0	0	0
1898	2385	3302	2509	1440	0	0	0	0	0	0	0	0
2385	3903	2986	2864	1898	0	0	0	0	0	0	0	0
2864	3314	2385	3943	3428	0	0	0	0	0	0	0	0

3314	3835	3557	4312	2864	0	0	0	0	0	0	0	0
3557	3314	82	3943	3122	0	0	0	0	0	0	0	0
3943	3903	3557	2864	82	0	0	0	0	0	0	0	0
3903	2385	82	3943	3302	0	0	0	0	0	0	0	0
3302	3903	1898	82	2378	0	0	0	0	0	0	0	0
2378	3302	1880	1440	0	0	0	0	0	0	0	0	0
1880	82	113	2834	2378	0	0	0	0	0	0	0	0
2363	3871	4243	118	2839	0	0	0	0	0	0	0	0
2839	2363	3210	118	4540	0	0	0	0	0	0	0	0
3210	118	2839	4366	2748	0	0	0	0	0	0	0	0
2748	2241	3210	118	3676	0	0	0	0	0	0	0	0
2834	2588	2348	1880	0	0	0	0	0	0	0	0	0
2348	3541	2815	113	2834	0	0	0	0	0	0	0	0
2815	3101	113	2398	2348	0	0	0	0	0	0	0	0
2398	2638	2815	1919	113	0	0	0	0	0	0	0	0
1919	2156	113	2398	1464	0	0	0	0	0	0	0	0
1464	1919	1686	113	1250	0	0	0	0	0	0	0	0
1250	1464	876	124	0	0	0	0	0	0	0	0	0
1686	2156	1679	1464	876	0	0	0	0	0	0	0	0
2156	3914	2638	1919	1686	0	0	0	0	0	0	0	0
2638	3509	3101	2156	2398	0	0	0	0	0	0	0	0
3101	3058	2638	3541	2815	0	0	0	0	0	0	0	0
3541	3101	1246	2588	2348	0	0	0	0	0	0	0	0
2588	3541	2114	82	2834	0	0	0	0	0	0	0	0
3058	3509	3101	1246	0	0	0	0	0	0	0	0	0
3509	3914	3058	2638	1859	0	0	0	0	0	0	0	0
3914	3509	2156	1679	0	0	0	0	0	0	0	0	0
2114	1246	82	1651	2588	0	0	0	0	0	0	0	0
1651	1859	2114	1231	82	0	0	0	0	0	0	0	0
1231	1679	82	1651	876	0	0	0	0	0	0	0	0
876	1686	1231	82	1250	0	0	0	0	0	0	0	0
1246	3058	1859	3541	2114	0	0	0	0	0	0	0	0
1679	3914	1859	1686	1231	0	0	0	0	0	0	0	0
1365	647	1590	118	968	0	0	0	0	0	0	0	0
1590	118	1365	1170	1799	0	0	0	0	0	0	0	0
1170	823	1590	118	1355	0	0	0	0	0	0	0	0
823	630	118	1419	1170	0	0	0	0	0	0	0	0
1182	1614	1419	129	689	0	0	0	0	0	0	0	0
1614	1355	1182	1814	0	0	0	0	0	0	0	0	0
1814	1799	689	1614	1360	0	0	0	0	0	0	0	0
1360	968	460	1814	0	0	0	0	0	0	0	0	0
689	59	1182	460	1814	0	0	0	0	0	0	0	0
968	1365	1799	1360	305	0	0	0	0	0	0	0	0
1355	1799	1614	1419	1170	0	0	0	0	0	0	0	0
1799	1590	1355	968	1814	0	0	0	0	0	0	0	0
2276	2762	3232	0	0	0	0	0	0	0	0	0	0
2762	2276	1028	0	0	0	0	0	0	0	0	0	0
3232	2276	0	0	0	0	0	0	0	0	0	0	0
3665	3692	3264	0	0	0	0	0	0	0	0	0	0
3264	1032	3665	0	0	0	0	0	0	0	0	0	0
3692	3665	0	0	0	0	0	0	0	0	0	0	0
1028	2762	164	0	0	0	0	0	0	0	0	0	0
1032	113	3264	0	0	0	0	0	0	0	0	0	0
1419	823	278	1355	1182	0	0	0	0	0	0	0	0
1859	3509	1679	1246	1651	0	0	0	0	0	0	0	0
1210	610	848	173	373	0	0	0	0	0	0	0	0
1632	767	1504	348	610	0	0	0	0	0	0	0	0
1944	1824	341	236	610	0	0	0	0	0	0	0	0
610	1504	348	341	236	1944	1632	1937	118	82	240	1747	1210

Face Vectors by Faces

Face	Face vector								
9	0	0	0	118	9	82	0	0	0
11	0	0	0	164	11	113	0	0	0
16	0	0	0	164	16	113	0	0	0
25	0	689	164	38	25	59	460	305	0
38	460	188	305	89	38	164	25	647	0
59	0	1182	25	164	59	129	689	460	0
89	305	118	38	188	89	647	0	164	0
129	0	1419	164	278	129	59	1182	689	0
188	647	932	118	417	188	89	164	2241	38
278	1182	560	1419	630	278	164	129	823	0
417	164	2311	2241	932	417	188	0	118	0
630	1419	118	278	560	630	823	0	164	0
932	2424	1393	2311	840	932	417	164	188	2241
560	823	1824	118	1190	560	630	164	341	278
840	164	1937	2424	1393	840	932	0	2311	0

1190	164	1944	341	1824	1190	560	0	118	0
1393	236	1824	1937	1494	1393	840	164	932	2424
1824	341	1393	1944	1494	1824	1190	164	560	236
1494	164	1944	236	1824	1494	1393	0	1937	0
1937	1494	4346	348	3607	1937	1393	236	3155	840
2424	3676	1393	2311	840	2424	1937	3469	932	0
2311	3469	840	2241	932	2311	2424	3676	417	2748
2241	3676	932	118	417	2241	2311	2748	188	0
647	968	188	1365	89	647	118	305	38	0
305	25	89	968	647	305	38	460	1365	1360
460	968	38	305	689	460	1360	25	59	1814
164	840	1494	932	1824	164	1393	560	1190	630
236	0	1824	1937	1494	236	1944	610	1393	0
341	0	1824	118	1190	341	1944	610	560	0
118	1190	3882	188	3455	118	560	1504	3871	1095
173	0	373	1210	610	173	82	251	124	0
251	1210	82	124	173	251	373	0	113	0
373	169	848	569	113	373	1210	251	173	124
569	1210	240	169	848	569	373	0	113	0
848	0	373	1210	610	848	240	569	169	0
82	2378	3581	3557	610	82	3903	2114	2834	1729
124	173	1464	1250	82	124	113	251	876	373
113	1903	2834	1919	1032	113	2815	2398	2378	1250
169	1440	2509	1903	240	169	113	569	848	373
240	2723	4578	3404	610	240	3835	2986	3140	1903
348	0	767	1937	522	348	1632	610	2439	0
522	1958	1632	2439	767	522	348	0	1937	0
767	2439	1504	1632	1095	767	522	1958	348	2033
1095	118	1632	2033	767	1095	1504	0	1958	0
1504	0	767	118	1095	1504	1632	610	2033	0
1958	3384	1095	2033	767	1958	2439	3797	522	2530
2439	3797	767	1958	522	2439	1937	3384	348	0
2229	0	1285	1747	610	2229	240	2723	2707	0
2723	1747	1736	2707	1285	2723	2229	0	240	0
2707	2229	1285	2723	1736	2707	1747	1729	1271	901
1729	1747	1736	2707	1271	1729	901	0	82	0
901	0	1271	1747	610	901	82	1729	2707	0
1285	2707	3162	240	3404	1285	1736	2723	2229	0
1736	2723	3404	1271	3162	1736	1285	2707	1705	1729
1271	2707	3162	82	1705	1271	1736	1729	901	0
1720	2673	2187	2204	2175	1720	2660	0	82	0
2204	3983	3811	3140	2187	2204	2673	1720	2175	2660
2660	4326	3122	3581	82	2660	2673	1720	2175	2204
3140	2673	2187	2204	3811	3140	3983	0	240	0
3581	2673	4312	2660	3122	3581	4326	0	82	0
3983	4326	4063	4578	240	3983	2673	3140	3811	2204
4326	3983	4063	4578	4312	4326	2673	3581	3122	2660
4578	2673	4312	3983	4063	4578	4326	0	240	0
4312	4578	3835	3122	3314	4312	4063	4326	3557	3581
3122	2660	3314	82	3557	3122	4312	3581	4326	0
2175	2204	3162	82	1705	2175	2187	1720	2660	0
2673	3140	4578	2660	4326	2673	3983	2204	3581	1720
3155	4175	4168	3789	4003	3155	3607	0	1937	0
3607	4443	4258	4168	4346	3607	3155	1937	4003	3789
4003	3789	3607	4168	3882	4003	3155	4175	3455	3009
4346	4243	4168	4443	4258	4346	3607	0	1937	0
3882	118	4168	3009	4003	3882	3455	0	4175	0
4258	4443	3607	4168	4346	4258	3871	4243	3455	2363
3455	3009	4258	4168	3882	3455	3871	118	4003	2363
3871	118	4168	2363	4258	3871	3455	0	4243	0
4243	4263	4346	2363	4258	4243	4443	4540	3871	2839
4443	4540	4258	4243	4346	4443	1937	4263	3607	0
3789	3797	4003	4175	3155	3789	1937	3384	3607	0
4168	3871	4346	3607	4258	4168	4003	3455	3882	3155
3384	0	4175	1937	3789	3384	2439	3797	1958	0
3797	2439	3789	3384	4175	3797	1958	2530	3009	2033
4175	3384	3882	3009	4003	4175	3789	3797	3155	2530
3404	0	2187	3811	3162	3404	240	1285	1736	0
3811	2204	3162	240	3404	3811	2187	3140	3983	0
3162	1285	3811	2187	3404	3162	1705	1736	2175	1271
1747	0	2723	901	610	1747	2229	2707	1729	0
1705	0	2187	2175	3162	1705	82	1271	1736	0
2187	3140	3404	2175	3162	2187	3811	2204	1705	1720
2033	3797	767	118	1095	2033	1958	2530	1504	0
2530	0	4175	118	3009	2530	2033	3797	1958	0
3009	3797	4003	118	3882	3009	4175	2530	3455	0
3469	0	2311	1937	2424	3469	3888	3676	4366	0

3888	0	4540	3469	1937	3888	4263	4366	3676	0
4263	0	4243	1937	4443	4263	3888	4540	4366	0
4540	3888	4443	2839	4243	4540	4263	4366	2363	3210
4366	2839	4263	4540	3888	4366	3210	3676	3469	2748
3676	3888	2424	4366	2311	3676	3469	2748	2241	3210
4063	3983	3314	240	3835	4063	4312	4578	4326	0
3835	0	4312	3428	3314	3835	240	4063	2864	0
3428	0	3314	2864	3835	3428	2986	240	2385	0
2986	0	2864	3428	2385	2986	240	2509	1898	0
2509	169	2385	240	2986	2509	1898	1903	1440	0
1903	113	1898	169	2509	1903	1440	0	240	0
1440	1880	3302	2378	1898	1440	113	1903	2509	169
1898	2378	3903	2509	2385	1898	3302	1440	2986	1903
2385	3302	3943	2864	3903	2385	2986	1898	3428	2509
2864	3557	3903	3943	3314	2864	2385	3428	3835	2986
3314	4063	3943	4312	3835	3314	3557	2864	3428	3122
3557	0	4312	3943	3314	3557	82	3122	2864	0
3943	0	3314	2864	3903	3943	3557	82	2385	0
3903	0	2864	3943	2385	3903	82	3302	1898	0
3302	1440	2385	82	3903	3302	1898	2378	1880	0
2378	113	1898	1440	3302	2378	1880	0	82	0
1880	2348	3302	2834	82	1880	113	2378	2588	1440
2363	4540	4258	118	3871	2363	4243	2839	3455	0
2839	0	4243	118	2363	2839	3210	4540	4366	0
3210	0	4540	4366	118	3210	2839	2748	3676	0
2748	0	2311	118	2241	2748	3210	3676	4366	0
2834	113	3541	1880	2588	2834	2348	0	82	0
2348	1880	3101	113	3541	2348	2815	2834	2588	0
2815	0	2638	2398	3101	2815	113	2348	3541	0
2398	0	3101	1919	2638	2398	2815	113	2156	0
1919	0	2638	2398	2156	1919	113	1464	1686	0
1464	124	2156	113	1919	1464	1686	1250	876	0
1250	113	1686	124	1464	1250	876	0	82	0
1686	1231	3914	1464	2156	1686	1679	876	1919	1250
2156	2398	3509	1919	3914	2156	2638	1686	1679	1464
2638	2815	3914	2156	3509	2638	3101	2398	3058	1919
3101	2398	3509	3541	3058	3101	2638	2815	1246	2348
3541	2114	3058	2588	3101	3541	1246	2348	2815	2834
2588	1880	1246	82	3541	2588	2114	2834	2348	0
3058	3541	2638	1246	3509	3058	3101	0	1859	0
3509	1679	3101	2638	3914	3509	3058	1859	2156	1246
3914	1686	2638	1679	3509	3914	2156	0	1859	0
2114	0	1859	1651	1246	2114	82	2588	3541	0
1651	0	1679	1231	1859	1651	2114	82	1246	0
1231	0	1859	1651	1679	1231	82	876	1686	0
876	124	1679	82	1686	876	1231	1250	1464	0
1246	1651	3509	3541	3058	1246	1859	2114	3101	2588
1679	1651	3509	1686	3914	1679	1859	1231	2156	876
1365	0	1799	118	647	1365	1590	968	305	0
1590	0	1355	1170	118	1590	1365	1799	968	0
1170	0	1799	118	823	1170	1590	1355	1419	0
823	1355	560	1419	630	823	118	1170	278	0
1182	1355	278	129	1614	1182	1419	689	59	1814
1614	689	1799	1814	1355	1614	1182	0	1419	0
1814	968	1355	1614	1799	1814	689	1360	1182	460
1360	305	1799	1814	968	1360	460	0	689	0
689	1614	129	460	59	689	1182	1814	25	1360
968	460	647	1360	1365	968	1799	305	1590	1814
1355	1182	823	1419	1799	1355	1614	1170	1590	1814
1799	1614	1365	968	1590	1799	1355	1814	1170	1360
2276	0	0	0	2762	2276	3232	0	0	0
2762	0	0	0	2276	2762	1028	0	0	0
3232	0	0	0	2276	3232	0	0	0	0
3665	0	0	0	3692	3665	3264	0	0	0
3264	0	0	0	1032	3264	3665	0	0	0
3692	0	0	0	3665	3692	0	0	0	0
1028	0	0	0	2762	1028	164	0	0	0
1032	0	0	0	113	1032	3264	0	0	0
1419	129	630	1355	823	1419	278	1182	1170	1614
1859	2114	3914	1246	3509	1859	1679	1651	3058	1231
1210	0	569	173	610	1210	848	373	251	0
1632	0	1095	348	767	1632	1504	610	522	0
1944	0	1494	236	1824	1944	341	610	1190	0
610	0	0	341	1504	610	348	236	0	0

Face Vectors Normalised

Face Face vector

9	0.5	0.5	0.5	0.594	0.125	0.369	0.5	0.5	0.5
11	0.5	0.5	0.5	0.567	0.125	0.356	0.5	0.5	0.5
16	0.5	0.5	0.5	0.567	0.125	0.356	0.5	0.5	0.5
25	0.5	0.375	0.567	0.859	0.469	0.719	0.125	0.5	0.5
38	0.125	1	0.5	1	0.859	0.567	0.469	0.859	0.5
59	0.5	0.125	0.469	0.567	0.719	0.469	0.375	0.125	0.5
89	0.5	0.594	0.859	1	1	0.859	0.5	0.567	0.5
129	0.5	0.5	0.567	0.859	0.469	0.719	0.125	0.375	0.5
188	0.859	1	0.594	1	1	1	0.567	0.859	0.859
278	0.125	1	0.5	1	0.859	0.567	0.469	0.859	0.5
417	0.567	0.625	0.859	1	1	1	0.5	0.594	0.5
630	0.5	0.594	0.859	1	1	0.859	0.5	0.567	0.5
932	0.891	1	0.625	1	1	1	0.567	1	0.859
560	0.859	1	0.594	1	1	1	0.567	0.969	0.859
840	0.567	0.654	0.891	1	1	1	0.5	0.625	0.5
1190	0.567	0.719	0.969	1	1	1	0.5	0.594	0.5
1393	0.969	1	0.654	1	1	1	0.567	1	0.891
1824	0.969	1	0.719	1	1	1	0.567	1	0.969
1494	0.567	0.719	0.969	1	1	1	0.5	0.654	0.5
1937	1	1	0.969	1	0.654	1	0.969	1	1
2424	0.25	1	0.625	1	0.891	0.654	0.531	1	0.5
2311	0.531	1	0.859	1	0.625	0.891	0.25	1	0.469
2241	0.25	1	0.594	1	0.859	0.625	0.469	1	0.5
647	0.125	1	0.469	1	0.859	0.594	0.5	0.859	0.5
305	0.469	1	0.125	0.859	0.5	0.859	0.125	0.469	0
460	0.125	0.859	0.5	0.375	0.125	0	0.469	0.719	0
164	1	1	1	1	0.567	1	1	1	1
236	0.5	1	0.654	1	0.969	0.719	0.562	1	0.5
341	0.5	1	0.594	1	0.969	0.719	0.562	1	0.5
118	1	1	1	1	0.594	1	0.969	1	1
173	0.5	0	0.344	0.562	0.0938	0.369	0	0	0.5
251	0.344	0.369	0	0.0938	0	0	0.5	0.356	0.5
373	0	0.0938	0	0.356	0	0.344	0	0.0938	0
569	0.344	0.365	0	0.0938	0	0	0.5	0.356	0.5
848	0.5	0	0.344	0.562	0.0938	0.365	0	0	0.5
82	0	0	0.469	0.562	0.369	0.469	0.469	0	0
124	0.0938	0.109	0	0.369	0	0.356	0	0.109	0
113	0	0	0.469	0.875	0.356	0.469	0.219	0	0
169	0	0.109	0	0.365	0	0.356	0	0.0938	0
240	0	0	0.469	0.562	0.365	0.469	0.469	0	0
348	0.5	1	0.654	1	0.969	0.719	0.562	0.891	0.5
522	0.625	0.719	0.891	1	1	0.969	0.5	0.654	0.5
767	0.891	0.969	0.719	1	1	1	0.625	0.969	0.891
1095	0.594	0.719	0.891	1	1	0.969	0.5	0.625	0.5
1504	0.5	1	0.594	1	0.969	0.719	0.562	0.891	0.5
1958	0.531	1	0.891	1	0.625	0.891	0.25	1	0.531
2439	0.25	1	0.625	1	0.891	0.654	0.531	0.969	0.5
2229	0.5	0.109	0.344	0.562	0.0938	0.365	0	0	0.5
2723	0.344	0.375	0	0.109	0	0.0938	0.5	0.365	0.5
2707	0.0938	0.109	0	0.375	0	0.344	0	0.109	0.0938
1729	0.344	0.375	0	0.109	0	0.0938	0.5	0.369	0.5
901	0.5	0.109	0.344	0.562	0.0938	0.369	0	0	0.5
1285	0	0.75	0.365	0.469	0.109	0.375	0	0.0938	0.5
1736	0	0.469	0.109	0.75	0.375	0.109	0	0.469	0
1271	0	0.75	0.369	0.469	0.109	0.375	0	0.0938	0.5
1720	0.25	0.375	0	0.109	0	0	0.5	0.369	0.5
2204	0	0.109	0	0.375	0	0.25	0	0.109	0
2660	0	0.109	0	0.369	0	0.25	0	0.109	0
3140	0.25	0.375	0	0.109	0	0	0.5	0.365	0.5
3581	0.25	0.375	0	0.109	0	0	0.5	0.369	0.5
3983	0	0.109	0	0.365	0	0.25	0	0.109	0
4326	0	0.109	0	0.375	0	0.25	0	0.109	0
4578	0.25	0.375	0	0.109	0	0	0.5	0.365	0.5
4312	0	0.469	0.109	0.75	0.375	0.109	0	0.469	0
3122	0	0.75	0.369	0.469	0.109	0.375	0	0	0.5
2175	0	0.75	0.369	0.469	0.109	0.375	0	0	0.5
2673	0	0	0	0	0.25	0	0	0	0
3155	0.625	0.75	0.891	1	1	1	0.5	0.654	0.5
3607	0.891	1	0.75	1	1	1	0.654	1	0.891
4003	0.891	1	0.75	1	1	1	0.625	1	0.891
4346	0.625	0.75	0.891	1	1	1	0.5	0.654	0.5
3882	0.594	0.75	0.891	1	1	1	0.5	0.625	0.5
4258	0.891	1	0.75	1	1	1	0.625	1	0.891
3455	0.891	1	0.75	1	1	1	0.594	1	0.891
3871	0.594	0.75	0.891	1	1	1	0.5	0.625	0.5
4243	0.531	1	0.891	1	0.625	0.891	0.25	1	0.531
4443	0.25	1	0.625	1	0.891	0.654	0.531	1	0.5

3789	0.25	1	0.625	1	0.891	0.654	0.531	1	0.5
4168	1	1	1	1	0.75	1	1	1	1
3384	0.5	0.625	0.654	0.891	0.531	0.891	0.25	0.625	0.5
3797	0.891	0.891	0.531	0.625	0.25	0.625	0.531	0.891	0.891
4175	0.531	1	0.891	1	0.625	0.891	0.25	1	0.531
3404	0.5	0.375	0.109	0.75	0.469	0.365	0.109	0.375	0.5
3811	0	0.75	0.365	0.469	0.109	0.375	0	0	0.5
3162	0.109	0.109	0.375	0.469	0.75	0.469	0.375	0.109	0.109
1747	0.5	0	0.0938	0.562	0.344	0.0938	0	0	0.5
1705	0.5	0.375	0.109	0.75	0.469	0.369	0.109	0.375	0.5
2187	0	0.469	0.109	0.75	0.375	0.109	0	0.469	0
2033	0.25	1	0.594	1	0.891	0.625	0.531	0.969	0.5
2530	0.5	0.625	0.594	0.891	0.531	0.891	0.25	0.625	0.5
3009	0.25	1	0.594	1	0.891	0.625	0.531	1	0.5
3469	0.5	0.625	0.654	0.891	0.531	0.781	0.25	0.5	0.5
3888	0.5	0.25	0.531	0.654	0.781	0.531	0.5	0.25	0.5
4263	0.5	0.625	0.654	0.891	0.531	0.781	0.25	0.5	0.5
4540	0.781	0.891	0.531	0.625	0.25	0.531	0.5	0.891	0.75
4366	0.531	0.531	0.25	0.781	0.5	0.75	0.25	0.531	0.469
3676	0.781	0.891	0.5	0.625	0.25	0.531	0.469	0.859	0.75
4063	0	0.75	0.365	0.469	0.109	0.375	0	0	0.5
3835	0.5	0.375	0.219	0.75	0.469	0.365	0.109	0.5	0.5
3428	0.5	0.75	0.5	0.469	0.219	0.469	0.365	0.75	0.5
2986	0.5	0.5	0.219	0.75	0.469	0.365	0.109	0.375	0.5
2509	0	0.75	0.365	0.469	0.109	0.375	0	0	0.5
1903	0.356	0.375	0	0.109	0	0	0.5	0.365	0.5
1440	0	0.109	0	0.375	0	0.356	0	0.109	0
1898	0	0.469	0.109	0.75	0.375	0.109	0	0.469	0
2385	0.109	0.219	0.5	0.469	0.75	0.469	0.375	0.219	0.109
2864	0.469	0.469	0.219	0.75	0.5	0.75	0.219	0.469	0.469
3314	0.109	0.219	0.375	0.469	0.75	0.469	0.5	0.219	0.109
3557	0.5	0.375	0.219	0.75	0.469	0.369	0.109	0.5	0.5
3943	0.5	0.75	0.5	0.469	0.219	0.469	0.369	0.75	0.5
3903	0.5	0.5	0.219	0.75	0.469	0.369	0.109	0.375	0.5
3302	0	0.75	0.369	0.469	0.109	0.375	0	0	0.5
2378	0.356	0.375	0	0.109	0	0	0.5	0.369	0.5
1880	0.109	0.109	0	0.369	0	0.356	0	0.109	0
2363	0.25	1	0.594	1	0.891	0.625	0.531	1	0.5
2839	0.5	0.625	0.594	0.891	0.531	0.75	0.25	0.5	0.5
3210	0.5	0.25	0.5	0.594	0.75	0.531	0.469	0.25	0.5
2748	0.5	0.625	0.594	0.859	0.469	0.75	0.25	0.5	0.5
2834	0.356	0.5	0	0.109	0	0.109	0.5	0.369	0.5
2348	0	0.875	0.356	0.5	0.109	0.469	0	0.109	0.5
2815	0.5	0.625	0.219	0.875	0.469	0.356	0.109	0.5	0.5
2398	0.5	0.875	0.469	0.625	0.219	0.469	0.356	0.875	0.5
1919	0.5	0.625	0.219	0.875	0.469	0.356	0.109	0.5	0.5
1464	0	0.875	0.356	0.469	0.109	0.5	0	0.109	0.5
1250	0.356	0.5	0	0.109	0	0.109	0.5	0.369	0.5
1686	0.469	1	0.109	0.875	0.5	0.875	0.109	0.469	0
2156	0.219	1	0.469	1	0.875	0.625	0.5	0.875	0.109
2638	0.469	1	0.875	1	0.625	0.875	0.219	1	0.469
3101	0.219	1	0.5	1	0.875	0.625	0.469	0.875	0.109
3541	0.469	1	0.109	0.875	0.5	0.875	0.109	0.469	0
2588	0	0.875	0.369	0.5	0.109	0.469	0	0.109	0.5
3058	0.5	0.625	0.875	1	1	0.875	0.5	0.625	0.5
3509	0.875	0.875	0.625	1	1	1	0.625	0.875	0.875
3914	0.5	0.625	0.875	1	1	0.875	0.5	0.625	0.5
2114	0.5	0.625	0.219	0.875	0.469	0.369	0.109	0.5	0.5
1651	0.5	0.875	0.469	0.625	0.219	0.469	0.369	0.875	0.5
1231	0.5	0.625	0.219	0.875	0.469	0.369	0.109	0.5	0.5
876	0	0.875	0.369	0.5	0.109	0.469	0	0.109	0.5
1246	0.219	1	0.5	1	0.875	0.625	0.469	0.875	0.109
1679	0.219	1	0.5	1	0.875	0.625	0.469	0.875	0.109
1365	0.5	0.375	0.594	0.859	0.469	0.719	0.125	0.5	0.5
1590	0.5	0.125	0.469	0.594	0.719	0.469	0.375	0.125	0.5
1170	0.5	0.375	0.594	0.859	0.469	0.719	0.125	0.5	0.5
823	0.125	1	0.5	1	0.859	0.594	0.469	0.859	0.5
1182	0.125	0.859	0.469	0	0.125	0.5	0.375	0.719	0
1614	0.375	0.375	0	0.125	0	0.125	0.5	0.5	0.5
1814	0.125	0.125	0	0.375	0	0.375	0	0.125	0.125
1360	0.5	0.375	0	0.125	0	0.125	0.5	0.375	0.5
689	0	0.469	0.125	0.719	0.375	0.125	0	0.469	0
968	0.125	0.859	0	0.469	0.125	0.375	0.5	0.719	0
1355	0.125	0.859	0.5	0.375	0.125	0	0.469	0.719	0
1799	0	0.469	0.125	0.719	0.375	0.125	0	0.469	0
2276	0.5	0.5	0.5	0.75	0.875	0.625	0.5	0.5	0.5
2762	0.5	0.5	0.5	0.875	0.75	0.125	0.5	0.5	0.5

3232	0.5	0.5	0.5	0.875	0.625	0.5	0.5	0.5	0.5
3665	0.5	0.5	0.5	0.375	0.125	0.25	0.5	0.5	0.5
3264	0.5	0.5	0.5	0.875	0.25	0.125	0.5	0.5	0.5
3692	0.5	0.5	0.5	0.125	0.375	0.5	0.5	0.5	0.5
1028	0.5	0.5	0.5	0.75	0.125	0.567	0.5	0.5	0.5
1032	0.5	0.5	0.5	0.356	0.875	0.25	0.5	0.5	0.5
1419	0.469	1	0.125	0.859	0.5	0.859	0.125	0.469	0
1859	0.469	1	0.875	1	0.625	0.875	0.219	1	0.469
1210	0.5	0	0.0938	0.562	0.344	0.0938	0	0	0.5
1632	0.5	1	0.969	1	0.719	0.969	0.562	1	0.5
1944	0.5	1	0.969	1	0.719	0.969	0.562	1	0.5
610	0.5	0.5	0.969	0.969	0.562	0.969	0.969	0.5	0.5

Appendix 5. Published Work

This Appendix contains copies of several research works published in Journals and Conferences during the development of the system. They are ordered in chronological order, therefore it shows in some way the history about the development process of FEBAMAPP.

CONCURRENT ENGINEERING: Research and Applications

Application of Neural Networks in Feature Recognition of Mould Reinforced Plastic Parts

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Abstract: Feature recognition is an application dependant task, which has been mostly focused in production planning of machining process. It plays a fundamental role and usually is the first step in downstream activities concerning product development process such as design for manufacturing, design for assembly and process planning. This report presents a methodology to carry out recognition of design for manufacturing features of reinforced plastic components. A three-layer neural network system was created and trained using back-propagation-supervised learning to recognise nine of the most important design features related to this manufacturing process. Also, a methodology for pre-processing 3-D solid models such that geometrical and topological information of the part could be suitable as network input is presented. High performance of the net system was achieved on the recognition of the trained features as it was observed in several test parts

Key Words: feature recognition, neural network (NN), computer aided design (CAD), design for manufacturing (DFM), reinforced plastic, concurrent engineering (CE)

1. Introduction

Feature definition is process dependent. For this reason moulding features of reinforced plastic need to be characterised with the aim of identification and classification. The main objective of this work is to point out the capabilities of using a feed-forward Neural Network as a tool to carry out automatic feature recognition. This will allow an easy medium of evaluating the manufacturing process of reinforced plastic components

The concept of classification involves the learning of likeness and differences in patterns that are abstractions of objects in a population of non-identical artefacts. When it is determined that an object from a population P belongs to a known sub-population S, we say that pattern recognition has been achieved. The recognition of an individual object as belonging to a unique class is called identification. Classification is the process of grouping objects together into classes according to their perceived likeness or similarities. The subject area of pattern recognition includes both classification and recognition and belongs to the broader field of machine intelligence.

2. Background

Figure 1 depicts sub-populations $S1, \ldots, S4$ of a population P of non-identical objects, along with the processing that recognises a sample object. A pattern recogniser is a system to which a feature vector is given as input, as which operates on the feature vector to produce an output that is the unique identifier (name, number, code-word, vector, string, etc.) associated with the class to which the object belongs [1].

An automatic pattern recognition system is an operational system that minimally contains an input subsystem that accepts sample pattern vectors, and a decision-maker subsystem that decides the classes to which an input pattern vector belongs. If it also classifies, then it has a learning mode in which it learns a set of classes of the population from a sample of pattern vectors; that is, it partitions the population into the sub-populations that are the feature classes.

A feature is either an attribute or a function of one or more attributes. Features must be observable, in that they can either be measured, obtained as a function of measured variables, or estimated from measured values of correlated variables. In general, a pattern vector of attributes is converted to a feature vector of lower dimension that contains all of the essential information of the pattern. Feature vectors from the same class, however, are also different. Typically, the differences come from three sources: noise, bias or system error, and natural variation between objects within the same classes due to unknown variations of operators that create the objects.

The system is trained using a finite set of patterns called the training set. If the correct classification for these patterns

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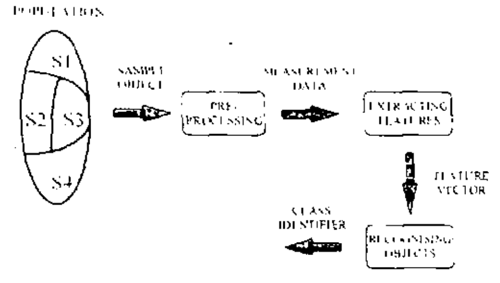

Figure 1. The recognition/classification process.

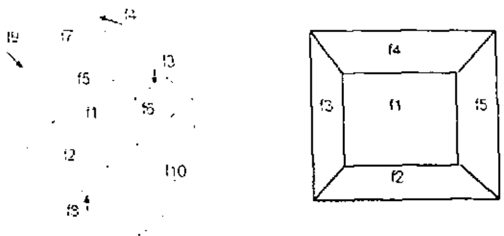

Figure 2. 2-D representation of a 3-D object.

is known then this is supervised learning, otherwise it is unsupervised learning. The performance of the system is evaluated using a different set of patterns known as the test set.

Development of a successful system requires a combination of careful research and planning, educated guesswork and outright trial-and-error approach.

The network of choice for most pattern recognition, signal processing and similar applications is a multi-layered feed-forward system called a Back-propagation network [2]. Back-propagation is probably the best approach to use if the input array is reasonably small and if the patterns to be learned do not vary greatly in their size or position in the input array.

Limitations of the back-propagation network include a long training time for large networks, a propensity not to train at all due to local minima in the error surface and limited ability to deal with input patterns that are not translational, rotational, and size invariant [3]. However, with proper conditions of the inputs, and by using recent improvements to the back propagation algorithm, these limitations can be overcome.

3. Experimental Work

The goal of this work is to evaluate the possibilities of using a feed-forward neural network to carry out identification of manufacturing related features. In this preliminary work nine features of plastic moulded objects were used to train the network. A total of 20 sample parts were evaluated and pre-processed so its geometrical information was transformed into a suitable vector to be used as input for the training of the neural network. Description of the pre-processing methodology used in this research is given below.

3.1 Data Pre-processing

The start point of the data pre-processing is to generate an SAT (Save As Text) file of the solid model. This format was chosen based in the following facts: it is standard in most of CAD modellers and it generates an easy to follow structure of the model information. Information goes all the way down from the solid, through faces and edges, and finally vertices and their X, Y, and Z co-ordinates.

The following sections will describe some of the concepts used in the attempted approach for a pre-processing algorithm of the solid's topological and geometrical data, such that it can be used as network input.

3.1.1 CONCEPT OF FACE SCORE GRAPH

An object in a boundary representation (B-rep) data structure consists of a set of faces and each face has neighbouring faces. In the B-rep scheme for solid models, the definition of the solid comes from combining the geometrical information about the faces, edges and vertices of an object with the topological data on how these are connected. This allows telling when a point is outside, inside or in the boundary of the object. In order to understand the relationship between each face and the other faces of the model, it is possible to convert a 3-D object into a 2-D face set [4]. An example of this is presented in Figure 2, where face 1 (f1) is represented in a 2-D face set.

3.1.2 CONCEPT OF CONVEXITY AND CONCAVITY

Chuang and Henderson [5] define concavity or convexity of a point on a B-rep element by defining an infinitesimally small spherical neighbourhood with the point at its centre. If the spherical neighbourhood is filled by more than half with solid material, then the point neighbourhood is concave. If the sphere is half filled with solid means that the neighbourhood is smooth, else it is convex. Following the previous definition, a face can be classified as convex or concave as it is shown in Figure 3.

Classification of an edge can be done on the basis of the angle between the faces sharing the edge, can be classified as smooth, convex or concave. A vertex, based on the types of edges sharing the vertex, can be classified as concave or convex. A convex vertex means more convex edges than concave edges sharing it. An illustration of this is shown in Figure 4.

In resume a face consists of a set of edges and vertices. Therefore, if a value is assigned to edges and vertices based on their geometric and topological information, then these values, which can be converted to a face, can be transformed into a score. This score includes, implicitly, the face information and the information of the edges and vertices on the face.

The evaluation formula can be written as

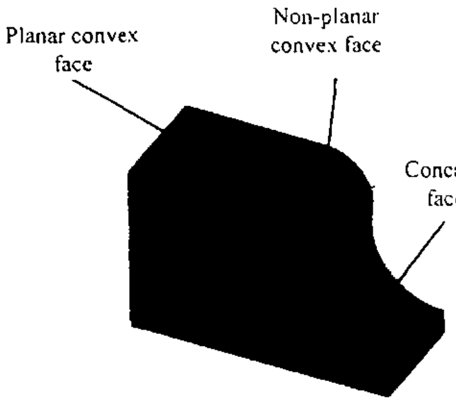

Figure 3. Face classification.

$$F_i = f(F_g, E_g, V_g, A_i)$$

where F_i is the face score, F_g is the face geometry information, E_g is the edge geometry information, V_g is vertex geometry information, and A_i is the adjacency among faces, edges and vertices.

3.1.3 CONCEPT OF FACE SCORE VECTOR

Hwang and Henderson [6] introduce the concept of face score vectors in order to represent features in a suitable way for neural network input, but a modified face score value assignation will be used in this paper. The reason supporting this modification is based on the presence of fillets that give origin to vertices with four edges and four adjacent faces, which are represented better with the proposed face vector. This assignment of values to each characteristic of the object in terms of faces, edges, loops and vertices is as shown in Table 1.

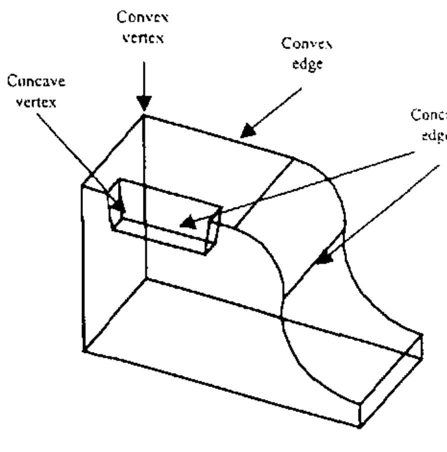

Figure 4. Types of edges and vertex.

Table 1. Assignment of values to obtain face values.

Edge Scores (E)	
Convex edge	+0.5
Concave edge	−0.5
Loop Scores (L)	
Positive inner loop	+1.0
Negative inner loop	−1.0
Face Geometry Scores (F_g)	
Planar surface	0.0
Convex surface	+2.0
Concave surface	−2.0

Using these values the vertex score is calculated by

$$V = \sum_{i=1}^{m} Ei$$

where V is the vertex score, Ei are the scores of the edges that intersect to form the vertex and m is the total number of edges sharing the vertex.

The face score is given by

$$F = \sum_{j=1}^{n} \frac{V_j}{n} + F_g + \sum_{k=1}^{l} L_k$$

where V_j is the vertex score, n is the number of vertices on the face, F_g is the face geometry score, L_k is the inner loop score and l is the number of inner loops present on the face.

3.2 Feature Definition

According to the previous section, a face score depends on the face and its boundary information. Therefore, since each face in the object has certain face score, a non-zero difference between a face score and its neighbouring face score indicates a topological or geometrical change between these faces, which form a region and the region may be defined as a feature [7]. It is up to the system developers to select the face that better defines each of the features they want to train the network with.

A slot feature is used in Figure 5 as example to show the face adjacency relationship in a solid model; face 1 [F_1 in Figure 5(a)] is used as the main face to define this particular feature.

Figure 5(b) shows a detail of the surrounding faces of F_1 in a corner so it is possible to observe that F_2 and F_3 have a sharing-edge relationship with F_1 but F_9 only shares a vertex with F_1. This fact will be used in the construction of the input vectors of the neural network.

Figure 6 shows the 2-D representation of face 1 and Table 2 contains the face score calculations for each of the faces defining this feature. The last column of this table contains the normalised values of the face scores ranging between 0 and

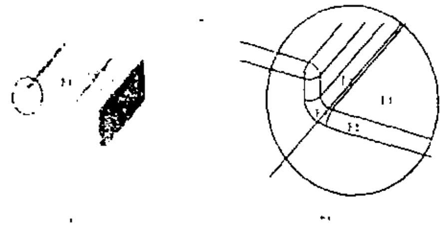

Figure 5. (a) Slot feature solid model. (b) wire-frame detail of the face adjacency

1. Normalised values (V_i) simplify the input in the neural net. The equation used to normalise the values is

$$V_i = (F_i + 4)/8$$

where F_i is the face score which maximum value is 4 for a face with just convex vertex and convex surface and (−4) for faces with concave edges and concave surface

Each face of the object has a nine-element face vector similar to the one shown in Figure 7, which is formed in accordance with the following rules:

- The fifth element of the vector is the face score of the face under consideration (main face).
- The immediately adjacent sharing-edge faces, faces F_2, F_3, F_4 and F_5 in Figure 6, with highest scores are in position fourth and sixth, and the next highest in position third and seventh respectively. If there is less than four faces sharing edges with the main face then those positions are set to zero. If there are more than four faces sharing edges then only the four highest scores are considered.
- Next, the highest score of the faces sharing only a vertex with the main face, faces F_6, F_7, F_8 and F_9 in Figure 6, are arranged in positions 2, 8, 1 and 9 accordingly to the same rules applied in the previous description.

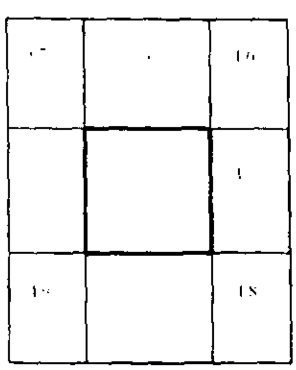

Figure 6. 2-D representation of the face adjacency relationship of face 1

Table 2. Face score calculation for the slot feature.

Face No.	Values	Result	Normalised
1	(0.5 + 0.5 − 0.5 − 0.5)/4 + 0.0 + 0.0	0.0	0.5
2, 3	(0.5 + 0.5 − 0.5 − 0.5)/4 − 2.0 + 0.0	−2.0	0.25
4, 5	(0.5 + 0.5 + 0.0 + 0.0)/4 + 2.0 − 0.0	2.25	0.781
6, 7, 8, 9	(0.5 + 0.5 + 0.0 + 0.0)/4 − 2.0 + 0.0	−1.75	0.281

Because faces far away from the main face play a minor role in determining the feature, a nine-element vector is considered to contain enough information for this purpose. The face score vectors for the remaining eight features considered in this paper are shown in Figures 8 to 15.

3.3 Network Architecture

SNNS (Stuttgart Neural Network Simulator), software from the University of Stuttgart in Germany, was used to construct the three layer Neural Network selected to carry out this work. The net architecture selected can be seen in Figure 16. Nine nodes or neurones corresponding to the nine elements of the face vectors form the first layer or input layer. This layer has a fixed number of nodes. Four nodes form the intermediate or hidden layer and finally, two nodes form the output layer, which allows having enough number of combination (4) of binary output (1 or 0) to represent the features.

Training was made under supervised theory using a data set corresponding to 20 part samples, which represent a total of 620 faces. From these data approximately 10% was saved for validation. Six thousand cycles of the complete data set was presented to each network in a random manner and the learning parameter was fixed at a value of 0.2. The learning function used was standard back-propagation.

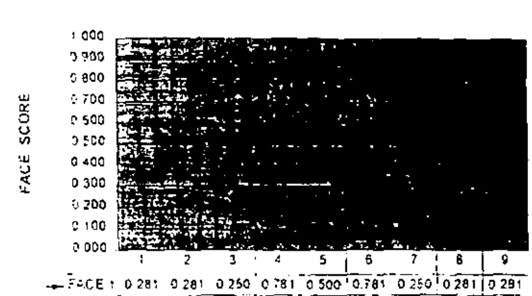

Figure 7. Face vector of face 1 representing the slot feature.

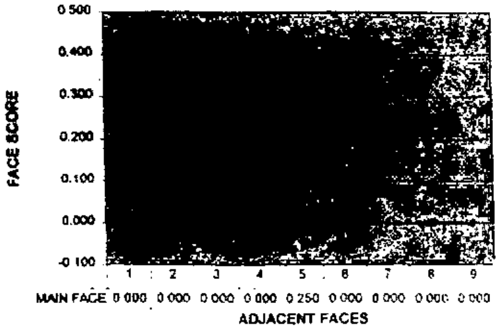

Figure 8. Pocket face vector.

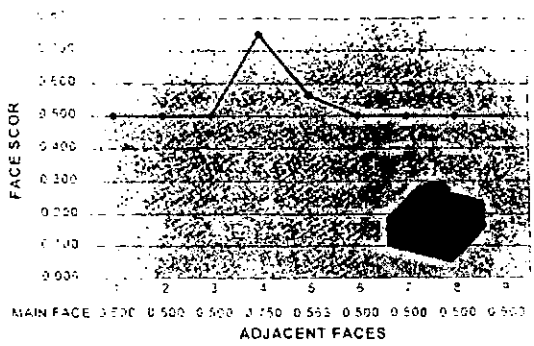

Figure 11. Boss face vector.

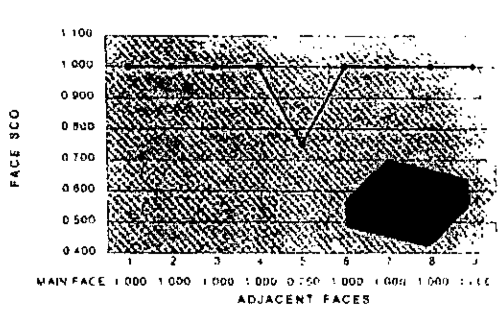

Figure 9. Protrusion face vector.

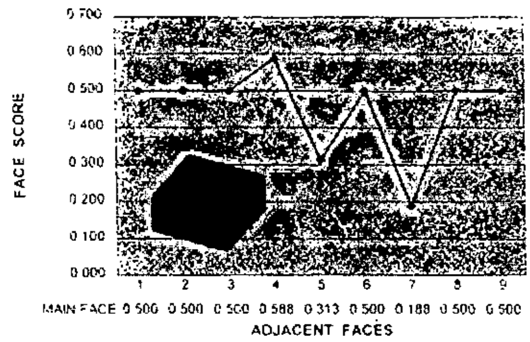

Figure 12. Through-Hole face vector.

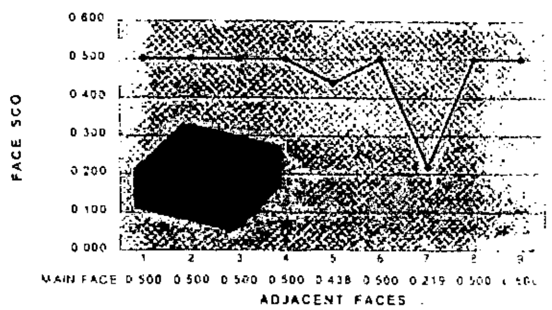

Figure 10. Circular-Pocket face vector.

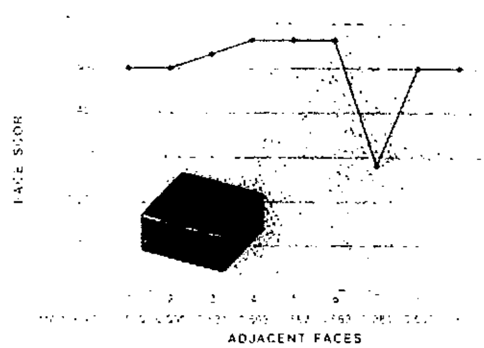

Figure 13. Irregular-Hole face vector.

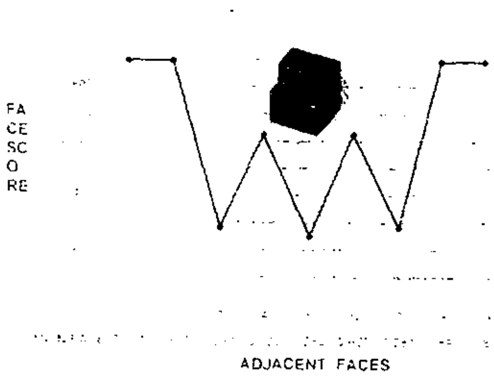

Figure 14. Step face vector

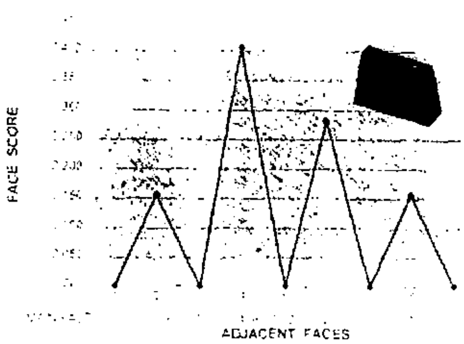

Figure 15. [illegible]-Step face vector

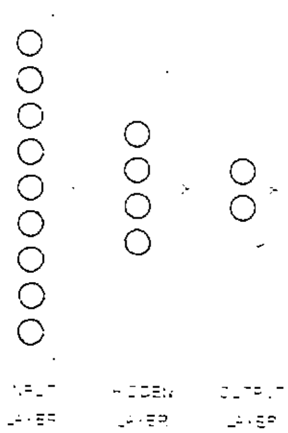

Figure 16. Architecture of the Neural Net used

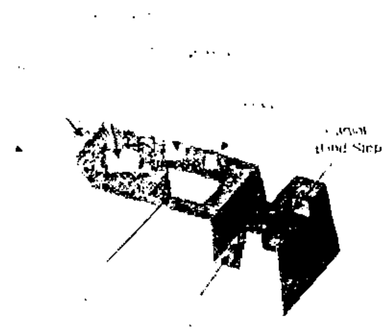

Figure 17. Sample Part 1, used to test the net performance.

4. Results and Discussion

Up to now, the learning process has been highly successful, which means that each of the networks recognises the feature it was trained to do so. The value of the threshold for recognition was fixed at 90% to allow for a reduction in the training time required by the net.

Finally, several complex parts were used to test the performance of the system. Figure 17 shows Sample Part 1, which has 142 faces, where seven of those faces correspond to trained features and one to a non-trained feature (Partial Blind-Step). Results from this evaluation are presented in Table 3 where it is possible to see the expected output and the actual output of each net. Only relevant faces of the part are presented in the table due to space limitations of this publication.

From the results it was observed that some features could be recognised even though they are part of more complex features, which suggest a need for sorting the feature recognition process such that no redundancy occurs. To solve this inconvenience a hierarchical order of the features was assumed such that when a main face for a given feature already belongs to a set of faces of a superior or equal feature, then the second feature recognition event is omitted.

This is the case for a Blind-Step feature, where the main

Table 3. Result of the evaluation of Sample Part 1.

Order	Feature	Expected Output	Actual Output
[illegible]	Protrusion	[01]	[0.00018 0.97204]
[illegible]	Boss	[01]	[0.00157 0.99094]
[illegible]	Circular Pocket	[01]	[0.00216 0.99706]
[illegible]	Pocket	[01]	[0.00564 0.95257]
[illegible]	Through Hole	[01]	[0.00481 0.99991]
[illegible]	Irregular Hole	[00]	[0.00074 0.00322] (no present in the part)
[illegible]	Step	[01]	[0.00149 0.99442]
[illegible]	Slot	[01]	[0.00189 0.99103]
[illegible]	Blind Step	[01]	[0.0218 0.97325]
—	Partial Blind-Step	[—]	[0.034 0.78231]*

*Obtained from Blind-Step net recogniser face may be recognised as part of a Pocket feature (see Table 3). Since it is assumed that the Pocket feature has a superior position 4 in the hierarchy than the Blind-Step feature 9, thus the second "feature recognition" event is not reported. The same case apply to the Irregular-Hole feature, where once it is recognised, all the faces belonging to the loop forming the hole are reported as a set of faces forming this particular feature. Therefore, posterior recognition of faces already in this set are not considered as a new feature being recognised. The hierarchical order of the features is given in the first column of Table 3.

5. Conclusions

Neural networks can be used as part of an automatic feature recognition system of manufacturing features of reinforced plastic components.

It is necessary to train one neural net for each feature to be recognised, which make the system easy to expand for the recognition of a major number of features or more complex ones if required. This would increase the time required to evaluate a particular part, since each face of the part has to be presented to each net for a particular feature recognition, but it will simplify the architecture and training of the system.

High performance of the system was evident during the feature recognition applied to the sample components used in this work, where all trained features were recognised.

Further work is underway regarding three fundamental areas of the system developing related to this research. First, the pre-processing of the SAT file is being automated such that time required for creation of the face vectors could be reduced. A program written in C++ is being developed for this purpose, which main goal is the pre-processing of the SAT files leading to the automatic generation of face vectors to be used as neural net input.

Second, developing of the interface between the neural net and the 3D modeller such that visual feedbacks of the recognition process can be achieved. Alternatives being studied for this interface development are C++ programming and Autolisp.

Finally, performance of the system will be evaluated regarding the generalisation of the recognition process under the presence of complex or combined features without previous training of the net.

Acknowledgements

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HYBRID TEXT FILE – NEURAL NETWORK FEATURE RECOGNITION SYSTEM

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ABSTRACT

Computer Aided Design (CAD) systems typically represent the geometry and topology of the part model in terms of low level product definition, which makes it very difficult to perform Automated Engineering Analysis (AEA) in downstream applications. Feature-based systems have demonstrated potential in creating interactive design environments and in automating the geometric reasoning required in applications such as manufacturability evaluation or design for manufacturing (DFM).

A methodology is presented to perform automatic recognition of features related to manufacturing processes of plastic components using a text file (SAT) and a neural-network hybrid system. The first phase of the feature recognition task is the processing of the model SAT file, where geometric and topological information of faces, edges and vertices is used to represent the model as a series of *face vectors*. Each face vector containing information of one face and its surrounding faces in the object.

The second phase of the process is presenting the face vectors to a trained three-layer feed-forward Neural Network system for the feature recognition, where one neural net is used for each of the features to be recognised.

A brief introduction of the feature recognition topic is presented in the first part of the paper, followed by a description of the part representation used in this research. Next, algorithms for the SAT file processing and description of the neural net architecture used are presented. In the last section results regarding feature identification in sample parts are shown to have a very good performance to over 99%.

Keywords: CAD, DFM, Feature recognition, Text file (SAT), Neural Network.

INTRODUCTION

Computer Aided Design (CAD) systems typically represent designed part as solid models, where the database represents the geometry and topology of the model in terms of low level product definition. These low level product definitions make it very difficult performing Automated Engineering Analysis (AEA). The power of AEA can be exploited to its fullest extent if the input of CAD data is in higher-level form, for instance as features.

The term feature is a highly context dependent concept. For the same part model, manufacturing features, assembly features, Finite Element Modelling (FEM) features, etc., might not be the same. The term 'feature' can be understood as "*a mathematical function of some topological and/or geometric variables whose values can be readily accessed or derived from the solid model of the part*" (Prabhakar and Henderson, 1992). Manufacturing features can be defined, without restrictions, as "*regions of a part with some manufacturing importance*" (Allada and Anand, 1996).

Feature-based systems have demonstrated potential in creating interactive design environments and in automating the geometric reasoning required in applications such as manufacturability evaluation. Designers have been using feature-based design system (FBDS) mainly based on two different approaches, the design by features approach and the automatic feature recognition approach.

In the design by features approach, information is stored during the design phase. The designer creates the part model using features present in a feature library obviating the need for a feature recognition procedure. However, the design by features approach has some drawbacks. In first place, all the possible features for any application cannot be stored in the feature library. In second place, the system calls for expertise on the designer to choose the best set of features to model the part, which in the counterpart is a constraint for the designer creativity by restricting him/her to the features present in the feature library.

Automatic feature recognition approach recognises features after the part is modelled on a CAD system. Typically, a specific geometry topology configuration is searched in the part model to infer the presence of a particular type of feature. These systems usually have complex algorithms and some of the approaches used include volume decomposition (Tseng and Joshi 1994), expert system (Donaldson and Jonathan 1993), graph-based approach (Laakko and Mantyla 1993), and the neural-network-based approach (Wang 1992, Prabhakar and Henderson 1992).

Some studies have indicated that pattern matching is not a feasible approach to feature recognition due to its computational intensity (Wang, 1992). Nevertheless, recently developing algorithms are giving a wider scope for the application of neural networks (NN) to feature recognition where the pre-processing of the model data plays a fundamental roll in the performance of the whole system.

The present work presents a methodology for pre-processing a solid model data stored in a text file (SAT) and feeding this information into a NN system where a specific geometry/topology configuration is searched to infer the presence of a particular type of feature in the model.

OBJECT REPRESENTATION

The selected object representation in this work is ACIS, the object-oriented three-dimensional (3D) geometric modelling engine from Spatial Technology Inc. which is designed to be used as the geometric foundation within end user 3D modelling applications. ACIS is a boundary-representation (B-rep) modeller, which means that it defines the boundary between solid material and empty space. ACIS separately represents the geometry and the topology of the objects, which provides the ability to determine whether a position is inside, outside or on the boundary of a volume. The model is implemented in C++ using a hierarchy of classes.

Geometry refers to the physical entities in the model, such as points, curves and surfaces, independent of their spatial relationship. Topology refers to the spatial relationship between the entities in the model. It describes how the entities are connected. A model object is any object that can be saved to and restored from a saved file.

An SAT file consists of one or two line header record, and an end marker for the file, and at least one data record between header and end marker. The header is followed by a sequence of entity records. These records are indexed sequentially starting at (0) zero. All top-level entities must appear before any other entities. Thereafter, the order is not significant. Pointers between entities are saved as integer index values, with NULL pointers represented by the value -1. ACIS pointer indices are preceded by $ is the .sat file. A complete description of the SAT file is available in the spatial web page (http:// www.spatial.com).

FILE PROCESSING ALGORITHMS

The SAT file is processed using a C++ program, which is able to obtain the relevant information required to perform the transformation of the model into *face vectors* based on each face characteristics. The evaluation function used to assign face scores can be written as:

$$F_s = f(F_{gv}, E_g, V_g, A_t) \qquad (1)$$

Where F_s is the face score, F_{gv} is the face geometry value, E_g is the edge geometry value, V_g stands for vertex geometry value, and A_t is the adjacency relationship among faces, edges and vertices.

In first place all faces in the object are identified and further information regarding Loops, Co-edges, edges and vertices present in each face are searched through the SAT file. Figure 1 presents a display of those entities and their spatial interrelations with each other.

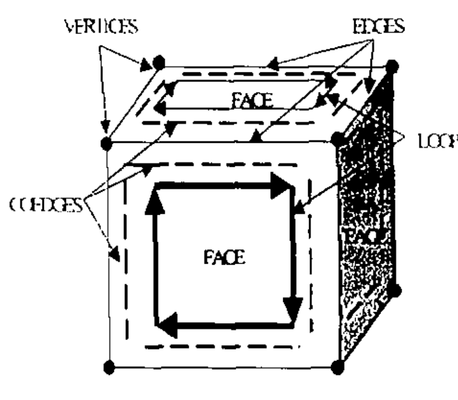

Figure 1. Faces, Loops, Coedges, Edges and Vertices

Five basic surfaces are used to create each model: plane surface, spline surface, sphere surface, cone surface and torus surface. F_{gv} is assigned according to surface convexity (+ 2.0) or concavity (- 2.0), considering that plane surfaces have $F_{gv} = 0$.

The next step is getting the information associated to each edge in the part and assigning to them an edge geometric score (E_g) based in their convexity (+ 0.5) or concavity (- 0.5). The sharing faces of the edge define this characteristic. Table 1 presents the different combinations of faces and the resulting edge geometric score (E_g).

Table 1. Face combination and E_g of edges.

	A	B	C	D	E	F	G	H
A	0	0	-0.5	0	0.5	-0.5	0.5	-0.5
B	0	0	0	-0.5	-0.5	0.5	0.5	-0.5
C	0.5	0	0	0	0	-0.5	0.5	0
D	0	-0.5	0	0	0	0.5	0	-0.5
E	0.5	-0.5	0	0	0.5	*	0.5	-0.5
F	-0.5	0.5	-0.5	0.5	*	0	-0.5	0.5
G	0.5	0.5	0.5	0	0.5	-0.5	0	0
H	-0.5	-0.5	0	-0.5	-0.5	0.5	0	0

A= convex cone; B= concave cone; C= convex sphere;

D= concave sphere; E= plane; F= Spline;

G= convex torus; H= concave torus.

(*) This combination may have convex or concave edges

The Vertex value (V_g) is assigned as function of the number and kind of edges sharing the vertex, according to the following equation:

$$V_g = (Cx - Cc) * 0.5 \qquad [2]$$

Where:

Cx = Number of convex edges sharing the vertex

Cc = Number of concave edges sharing the vertex

Next, a face score (F_s) is computed based in the face geometric value and the vertex value of the face according to the following equation:

$$Fs = \frac{\sum^{v} Fg}{n} + Fgv \qquad [3]$$

Where n is the total number of vertices belonging to the face under evaluation

Finally, a face vector (FV) is created, which consists of nine elements corresponding to the F_s of the face under evaluation and the F_s of the surrounding faces. Surrounding faces are classified as sharing-edge faces and sharing-vertex faces. Figure 2 shows the structure of the face vector.

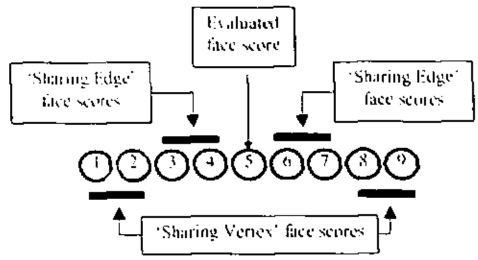

Figure 2. Face vector structure.

MATCHING FACE VECTORS TO FEATURES

After coding the solid model according to the rules and algorithm previously described, this information is used as input in the neural network system. Supervised learning of three layers feed-forward neural networks was used to carry out the feature recognition task. figure 3 shows a sketch of the NN architecture used. The feature patterns to be recognised are shown in figure 4.

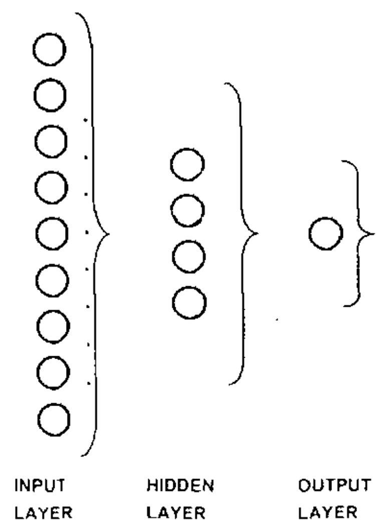

Figure 3. Neural Network architecture

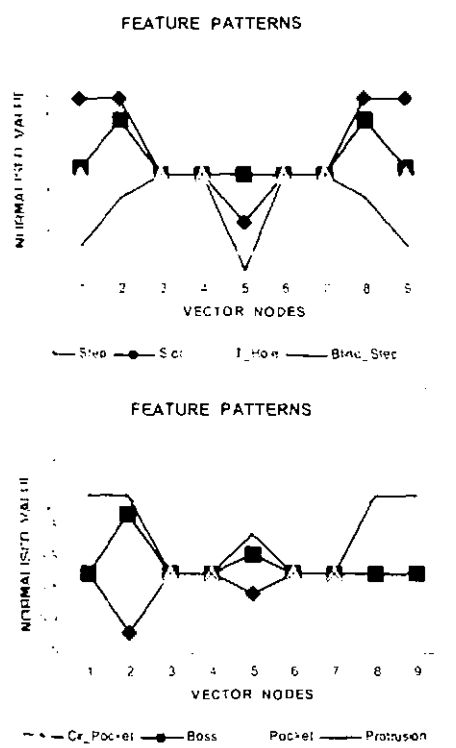

Figure 4. Feature patterns to be recognised.

The expected output of the NN is one (1) or zero (0) for recognised or non-recognised feature, respectively.

Training of the NN system was carried out using a data set of 15 sample parts with a total of 510 faces. 15% of the data was saved for validation and five thousands cycles of the complete data set was randomly presented to each network. Learning parameter of 0.2 and standard back-propagation learning function was used. Recognition threshold was fixed at 90%, which reduce the training time required by the net

RESULTS AND DISSCUSION

Several sample parts, selected from a reinforced plastic spray-lay-up manufacturing process, were used to test the performance of the system, showing a very high rate of recognition (100%) on the features the system was trained to do so.

Even though the face vectors have to be presented separately to each neural network for recognition of particular features, processing of the SAT file is required only once.

Figure 5 shows one of the sample parts used to test the performance of the system and table 2 contains the output of the recognition process corresponding to this sample component.

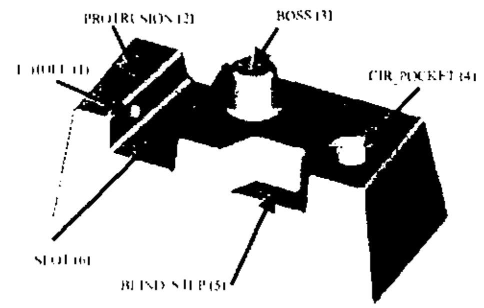

Figure 5. Sample part 1 used to test the system performance.

Table 2. Neural network outputs for sample part 1.

	FEATURES					
	1	**2**	**3**	**4**	**5**	**6**
F	0.50	1.00	0.50	0.50	0.13	0.53
A	0.65	1.00	0.88	0.13	0.63	0.78
C	0.50	0.50	0.50	0.50	0.50	0.50
E	0.50	0.50	0.50	0.50	0.50	0.50
V	0.13	1.00	0.88	0.63	0.00	0.75
E	0.50	0.50	0.50	0.50	0.50	0.50
C	0.50	0.50	0.50	0.50	0.50	0.50
T O	0.58	1.00	0.50	0.50	0.63	0.75
R	0.50	1.00	0.50	0.50	0.13	0.53
Target output	1.00	1.00	1.00	1.00	1.00	1.00
Actual output	0.99	0.95	0.97	0.94	0.98	0.98

In figure 6 it is possible to observe several features in a different layout for testing the feature recognition capacity of the system. Table 3 shows results corresponding to sample part 2.

Most of the parts used for testing the system were sintectic with the intention of putting together as many features in the same component as possible and avoiding interference between adjacent features, but also some real parts were used showing the same results.

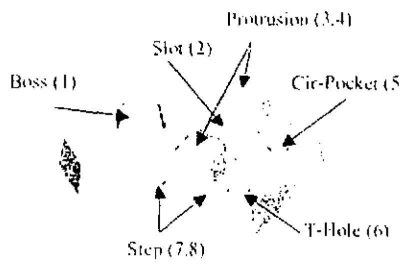

Figure 6. Sample part 2.

Table 3. Neural Network outputs for sample part 2.

	FEATURES							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
FACE VECTOR	0.50	0.53	1.00	1.00	0.50	0.50	0.89	0.89
	0.88	0.78	1.00	1.00	0.13	0.66	0.89	0.89
	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
	0.63	0.50	0.75	0.75	0.38	0.13	0.25	0.25
	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
	0.50	0.75	1.00	1.00	0.50	0.58	0.89	0.89
	0.50	0.53	1.00	1.00	0.50	0.50	0.89	0.89
T	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
A	0.998	[illegible]	0.999	0.999	0.996	0.999	[illegible]	0.997

T is the target neural network outputs, and A the actual outputs

CONCLUSIONS

On one side, the SAT file has proved to contain enough information, about the solid model, to be used as part of an automatic feature recognition system. On the other side, the face vector concept used in this research seems to be appropriated to represent the solid geometrical and topological characteristics leading toward a straightforward feature recognition algorithm using a neural network approach.

The system has proved also its capability to handle features under the presence of fillets, one of the main differences between plastic and traditional machined components.

The fact that one NN is required for each recognising feature allows the system to be easily updated adding new features to it and or adding a new set of features for a different application, if required.

Finally, based on the recognition rate it is possible to confirm that the hybrid Text File-Neural Network system shows high performance on this particular application of feature recognition.

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Automatic feature recognition on plastic components

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Summary

Computer Aided Design (CAD) systems typically represent the geometry and topology of the part model in terms of low level product definition, which makes it very difficult to perform Automated Engineering Analysis (AEA) in downstream applications. Feature based systems have demonstrated potential in creating interactive design environments and in automating the geometric reasoning required in applications such as manufacturability evaluation. Though, the number of features in a particular application are infinite, the good news is that they can be categorised into a finite number of classes.

A methodology is presented to perform automatic recognition of design features related to manufacturing processes of plastic components, where a specific geometry/topology configuration is searched in the part model by processing its Save As Text (SAT) file to infer the presence of a particular type of feature.

This process of feature recognition comprises three major tasks: first, feature definition, in which the rules for recognition are specified; second, feature classification, in which potential features are classified; and third, feature extraction, in which features are extracted from the solid model and stored for further analysis. A hybrid C++ and Neural Network (NN) system was created to perform the feature extraction task.

1. Introduction

The term feature is very context dependent, therefore for the same part model, manufacturing features, assembly features, finite element modelling (FEM) features, etc., might not be the same. The term 'feature' can be understood as *"a mathematical function of some topological and/or geometric variables whose values can be readily accessed or derived from the solid model of the part"* [1]. Also, Manufacturing features can be defined, without restrictions, as *"regions of a part with some manufacturing importance"* [2].

Automatic feature recognition systems recognise features after the part is modelled on a CAD system. Typically, after the geometric model is created a computer program processes the database to discover and extract specific geometry/topology to infer the presence of a particular type of feature. Various techniques have been developed to obtain this information directly from the geometric model database. Basically these techniques are based in comparing portions of the geometric model with predefined generic features to identify instances that match the predefined ones. These systems usually have complex algorithms.

One advantage of applying neural networks to feature recognition is that they are capable of learning by example [3]. This implies that they can be trained to perform recognition tasks by presenting them with examples rather than specifying the procedure. Another major advantage of neural networks is that they are relatively robust, and, if trained properly, can perform very well on noisy or incomplete input patterns.

In the remaining of the paper a detailed description of the feature definition and feature classification used in this research will be presented. Then, examples of the feature extraction task will show the performance of the proposed feature recognition system in the processing of a solid model of a plastic part. In the last section, conclusions will be presented along with a brief description of further work being carried out as part of this project.

2. Feature Definition

The approach used in this research to define the features is based on the geometrical characteristics of each face and its topological relationship with the adjacent faces of the object. Due to the presence of fillets a modified concept of the face-score (FS) introduced by Hwang [4] is necessary to capture the information of each face. A proposed face-vector (FV) of nine elements containing the FS of the evaluated face plus the FSs of its surrounding faces is used.

Two different kind of relationship between adjacent faces should be described as a foundation for the feature definition. In first place, a 'Sharing-Edge' relationship that occurs between two adjacent faces sharing an edge of the object and in second place, a 'Sharing Vertex' relationship, which occurs between two adjacent faces that share only a vertex of the object. Figure 1 shows a 2D representation of a 3D object where it is possible to observe examples of these two kinds of relationship between adjacent faces.

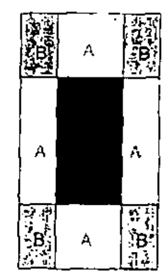

Figure 1. (A) Sharing-Edge (B) Sharing Vertex relationship between adjacent faces and evaluated face (F)

Face-score is a way to quantify geometrical characteristics of the faces in the object. Its value is based on three factors, Face-Geometric-Value (FGV), Edge-Score (ES) and the Vertex-Value (VV). Five basic surfaces are used to create each model: plane surface, spline surface, sphere surface, cone surface and torus surface. FGV is assigned in relation to the convexity (2.0), concavity (-2.0) and plane or undefined (0.0) characteristic of each surface.

The ES is also associated with the concavity (-0.5) or convexity (0.5) of the edges, which is defined by the combination of the faces sharing the edge. Table 1 presents the different combinations of faces and their resulting ES.

The VV is a number assigned relating to the number and kind of edges converging into the vertex according to equation 1.

$$VV = 0.5(Cx - Cc) \quad [1]$$

Where Cx and Cc are the number of convex and concave edges converging into the vertex. Finally, the FS is computed based on the FGV and the VV values of the face according to equation 2.

$$FS = \frac{\sum_{1}^{NV} VVi}{NV} + FGV \quad [2]$$

Where *NV* is the total number of vertecies in the face under evaluation.

	(CxC)	(CcC)	(CxS)	(CcS)	(P)	(S)	(CxT)	(CcT)
(CxC)	0.0	0.0	0.5	0.0	0.5	0.5	0.5	0.5
(CcC)	0.0	0.0	0.0	0.5	0.5	0.5	0.5	0.5
(CxS)	0.5	0.0	0.0	0.0	0.0	0.5	0.5	0.0
(CcS)	0.0	0.5	0.0	0.0	0.0	0.5	0.0	0.5
(P)	0.5	0.5	0.0	0.0	0.5	**	0.5	0.5
(S)	0.5	0.5	0.5	0.5	**	0.0	0.5	0.5
(CxT)	0.5	0.5	0.5	0.0	0.5	0.5	0.0	0.0
(CcT)	0.5	0.5	0.0	0.5	0.5	0.5	0.0	0.0

*Table 1. Face combination and corresponding ES. Convex cone (CxC), Concave cone (CcC), Convex sphere (CxS), Concave sphere (CcS), Plane (P), Spline (S), Convex Torus (CxT), Concave Torus (CcT). ** This options require a further evaluation*

Finally, a FV is created for each face in the object. Each face in the object will become the evaluated face, in turn, whose FS will be allocated to the fifth element of the FV. Then the adjacent 'Sharing-Edge' faces are considered and their corresponding FV will be allocated to the elements 4, 6, 3, 7 (from higher to lower score respectively).

In the event that there are less than four 'Sharing-Edge' faces, for a particular face, the remaining of these four elements will be set to zero. But, if there are more than four 'Sharing-Edge' faces, then only the four faces with the higher scores will be used in constructing the FV.

The other four elements of the FV will contain the FS of the adjacent 'Sharing Vertex' faces following the same pattern (2, 8, 1, 9) and rules applied to the assignment of the adjacent 'Sharing-Edge' face scores. Figure 2 shows a typical FV and its elements.

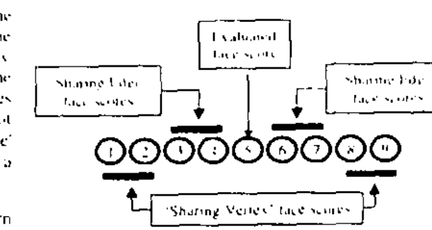

Figure 2. Typical Face Vector and its elements

Since each face has its own FV, which on expansion contains the information regarding the geometrical and topological characteristics of the evaluated face and its surrounding faces, then it is possible to say that faces with similar characteristics will have similar face vectors. This is the fact used to define different features, where each feature maps to a particular pattern or face vector.

3. Feature Classification

Following the procedure described in the previous section FVs where created and then particular faces were selected to represent each one of the features considered in this research. Figure 3 shows the different FVs representing those features.

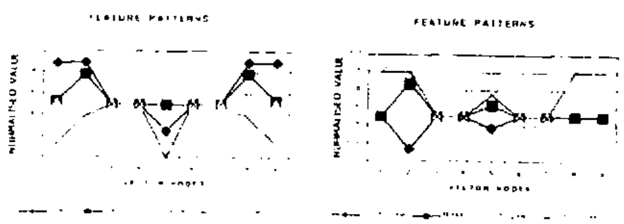

Figure 3. Face Vectors representing features

4. Feature Extraction

To perform feature extraction a CAD model of a component is created and its SAT file is processed using a C++ program, which is able to search the model database and get the relevant information required, transforming geometric and topological data into FVs of the part.

Then, the FVs are presented to the NN system, which is in charge of carrying on the pattern matching task. The NN system consists of one previously trained three layer network for each feature to be recognised. Figure 4 shows a sample part evaluated using the previous described system. Table 2 contains results of the feature recognition task, where the expected output of the NN is compared with its actual output. A threshold for recognition was selected.

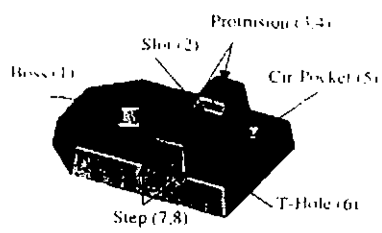

Figure 4. Sample part used for feature recognition

	FEATURES							
	1	2	3	4	5	6	7	8
FACE VECTOR	0.500	0.531	1.000	1.000	0.500	0.500	0.891	0.891
	0.875	0.781	1.000	1.000	0.125	0.663	0.891	0.891
	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	0.625	0.500	0.750	0.750	0.375	0.125	0.250	0.250
	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	0.500	0.781	1.000	1.000	0.500	0.583	0.891	0.891
	0.500	0.531	1.000	1.000	0.500	0.500	0.891	0.891
Target Output	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Actual Output	0.998	0.991	0.999	0.999	0.996	0.999	0.997	0.997

Table 2. Results of the feature recognition

5. Conclusions

A very effective hybrid system for automatic feature recognition on plastic components has been developed, which is based on the processing of the SAT file of the solid model and pattern matching using an ad hoc three-layer neural network system.

Some characteristics of the system deserve special mention. First, it performs very high performance 3D-feature recognition. Second, it is able to handle the presence of fillets, which is a main difference with current feature recognition systems used in machining process planning applications. Finally, it is simple to update the NN system for recognition of new features without affecting the previous training.

Further work is being carried out regarding visual feedback of recognition and to develop a rule-based feature evaluation module to analyse manufacturability of the models. Also, some work regarding recognition of more complex and/or interfering features is being done.

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FEBAMAPP: FEATURE – BASED MANUFACTURABILITY ANALYSIS OF PLASTICS PARTS

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ABSTRACT

This paper proposes a systematic and consistent methodology to perform manufacturability analysis of Reinforced Plastic Parts (RPP). The proposed methodology evaluates the part model in the early stages of the product development process considering the capabilities and constraints of available manufacturing processes, materials and tooling required in standard RPP production.

The lack of support from Computer Aided Design and Manufacture (CAD/CAM) into the reinforced plastics industry is the major motivation of this research. Critical Manufacturing Part Features (CMPF) are identified and the relationship between the model's geometrical information, the expert's geometric reasoning, and the knowledge about the involved manufacturing processes are clarified and set together in an efficient feature-rule-based manufacturability analysis system.

A prototype system named 'FEBAMAPP' is being developed. This system combines solid modelling (SM), automatic feature recognition (AFR), object oriented programming (OOP), and a rule-based system (RBS) in order to assess the manufacturability of the proposed design.

The analysis is focused in internal and external characteristics of the features, where potential manufacturing difficulties are identified and feed-back in terms of design suggestions is then used to advise the design process and improve the overall manufacturability of the part. Some virtual parts have been used in testing the prototype system showing promising results.

KEYWORDS: CAD/CAM, Concurrent Engineering (CE), Manufacturability Analysis, Knowledge–Based System (KBS), Feature-Based Design (FBD), Expert System (ES).

INTRODUCTION

Traditional method of developing products suffers from a lack of information at the later stages of the development process where the early decisions have a major influence increasing the lead-time and impacting the allocation of the project resources (Ching and Wong, 1999). Most of these problems could be avoided if the design team is able to make the early decisions with sufficient considerations regarding aspects such as available manufacturing processes, materials, tooling and labour.

Detailed information of product concepts is normally not available at early development stages, and thus decisions are made using qualitative information and judgement, requiring expert knowledge to direct the evaluation of the proposed design alternative (Rosenman, 1993). In traditional practice the product concept development relies on human experts, such as product designers, tool designers and manufacturing engineers who are required to have a high standard of specific knowledge, experience and judgement.

The planning and design functions can be performed very well by Knowledge-Based Systems (KBS) in the engineering and manufacturing areas of the product design (Ignizio, 1991). The product concept development and evaluation are predominantly based on the experience of designers. Extensive mathematical analysis is not often utilised, since analytical models are not available and calculations are also limited to satisfy empirical rules. Hence, the designers are required to have a high standard of specific knowledge and judgement.

Current KBS applications in solving moulding product design are relatively new and few. Research topics of capturing injection moulding part design features from CAD models, advising plastic material selection, automating the mould design process, etc., have become popular. Most of the existing systems such as CIMP (Jong and Wang, 1989), HyperQ/Plastic (Beiter et. al., 1991), and PLASSEX (Agrawal and Vasudevan, 1993) possess searching mechanisms and heuristic rules to assist designers in selecting a candidate material by both quantitative and qualitative evaluations. They were designed in a standalone manner, not integrated into the part design, mould design or process planning.

ICAD (Clinquegrana, 1990), DFIM (Zhang et. al., 1994), and IMDA (Borg and MacCallum, 1995) where systems developed for injection mould design. They require part design details, such as three-dimensional geometrical profile and dimensions, as compulsory inputs to these systems, so they can do part of the detailed product design work but are reported as not appropriate for the conceptual product design and new product development planning purposes (Wang et. al., 1995).

It has been recognised that feature-based modelling can bridge the gap between engineering design and manufacturing (Ling and Narayan, 1996). The information required by the different domains involved in the new product development process requires a common linkage among these domains so the product development cycle can be reduced. This linkage, in the form of features, can facilitate the automation of the design to manufacture process.

THE SYSTEM FRAMEWORK

Figure 1 presents the framework of the Feature-Based Manufacturability Analysis of Plastics Parts (FEBAMAPP) system. The system evaluates the model starting with the pre-processing of the text file of the part (ACIS file), goes through automatic feature recognition, evaluation of internal and external characteristics of all features identified and end up with a feed-back to the designer in terms of design suggestions. Design suggestions are focused on those features, which may represent problems at manufacturing stage and they do not attempt to be general design suggestions for the whole model.

The product concept development process is rather complex that requires a set of assumptions to simplify the task. The assumptions included in this system are that the market has been analysed, the need for a new product has been identified, design requirements and product constraints have been defined, and the functions of the mould reinforced part or components have been identified based on design requirements and product constraints. The FEBAMAPP system focuses on evaluating proposed models at the early stage of the product development process using a rule-based expert system.

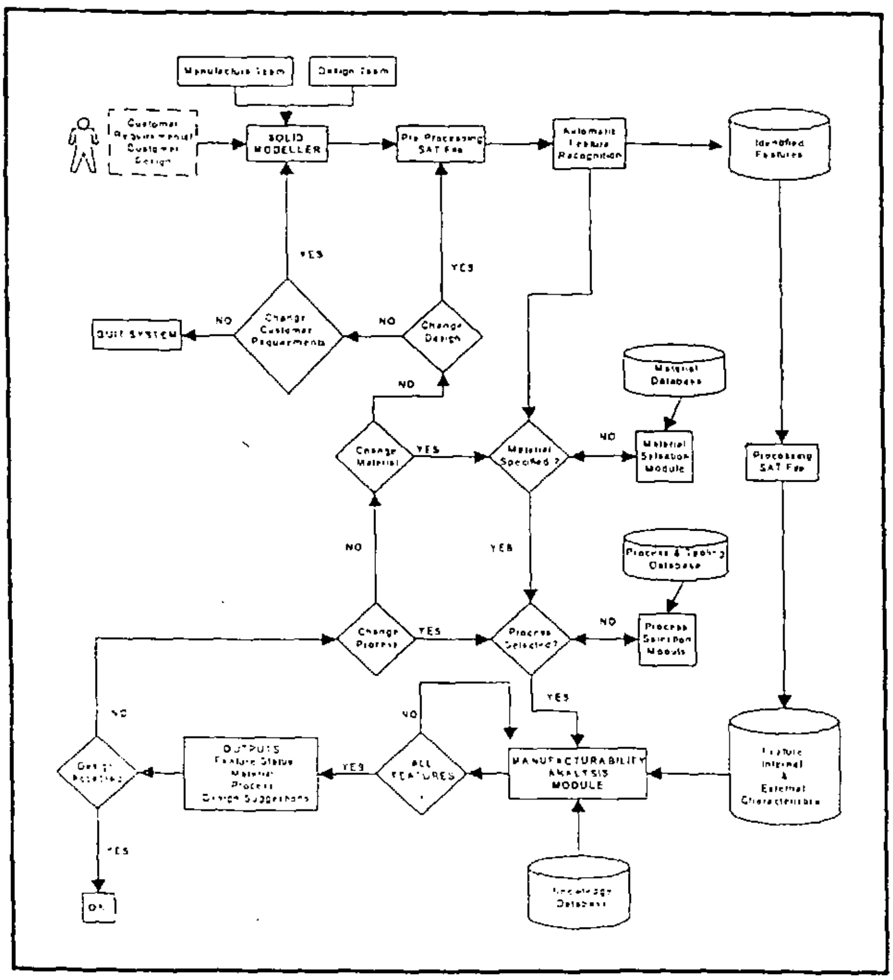


Figure 1. Framework of the FEBAMAPP system.

KNOWLEDGE-BASED SYSTEM DESIGN

Design rules can be seen as critical relationships between design requirements and process capabilities. Process capability data is usually compiled by manufacturing engineers and organised in such a way that constitutes the basis for design rules. These rules provide with the limiting conditions that determine whether a proposed design becomes unfeasible due to its cost, quality, lead-time, or combination of these characteristics.

Most of the explicit work in the plastic industry is considered commercially confidential, therefore it was necessary to perform a through analysis of mould and die design literature to obtain some detailed information concerning reinforced plastics product design and manufacture. Most of the information used to built the knowledge-based system and its explicit design and manufacturing rules were collected from the reinforced plastic enclosure industry, texts and handbooks related to this particular manufacturing process.

According to the human experts, the types of knowledge related to reinforced plastics manufacturing processes are usually represented in forms of equations, tables, rules of thumb and design constraints related to materials and/or processes. The frame-based representation method is used in FEBAMAPP to present the knowledge of a particular feature (object); while the rule-based knowledge representation is used to represent the decision logic and features mapping.

The declarative knowledge or facts used in FEBAMAPP can be broadly classified as follows.

- Feature knowledge (design constraints).
- Plastic material knowledge (plastic matrix).
- Reinforcing material knowledge (reinforcement fibre).
- Equipment and tooling knowledge (manufacturing processes).
- Mould's components design (knowledge and judgement).

The rules can be broadly categorised as follows.

- Rules for material selection.
- Rules for process selection.
- Rules for evaluation of internal characteristics of features.
- Rules for evaluation of external characteristics of features.

FEBAMAPP uses the forward chaining instead of backward chaining based upon its simplicity and better efficiency in execution. Typical forward chaining systems are used to solve problems oriented to data or diagnostic where the input facts are known and the user is looking for the derived output.

The inference process begins with the information currently provided by the pre-processing of the SAT file of the solid model of the part and draws conclusions, according to the conditional rules that it knows already. During this process, it may request further details from the user so proper selection of materials and manufacturing process can be used during the inference process. Eventually, it will arrive at logical consequences, which it then gives as its decision and a report in terms of design suggestions is generated.

The series of features considered for evaluation in this research are pocket, protrusion, circular-pocket, boss, through-hole, slot, step and blind-step. All of them fully supported by the feature recognition module developed as part of this research (Marquez et. al., 1999).

THE PROTOTYPE SYSTEM

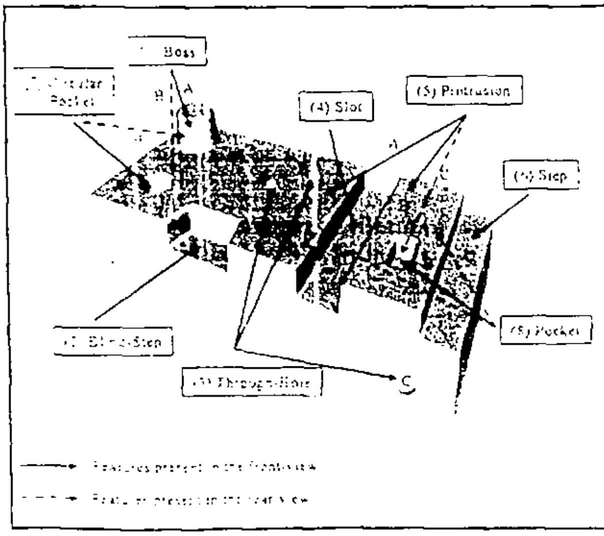
A prototype system is been developed as a Windows Application using Visual C++ according to the framework presented above and it consists of several modules as follows.

- Pre-processing of Sat file (PRESAT).
- Automatic feature recognition (AFR).
- Post-processing of the Sat file (POSTSAT).
- Material selection (MS).
- Process selection (PS).
- Manufacturability analysis (MA).
- Report generation (RG).

The system is designed to run the modules in sequential order. Modular reports of partial results from each module are available to the designer if required.

VALIDATION OF THE SYSTEM

Validation of the system was made using virtual sample parts and very promising results have been obtained. Figure 2 shows one of these sample parts where it is possible to observe the presence of several features, previously identified by the feature recognition module in the manufacturability analysis process. Threshold for recognition on the Neural Network System (NNS) was set to 0.9 (90%) to reduce the training time required, and also to allow the NNS to generalise under the presence of unknown data. The precision for identification of features in this particular example range between 93.2% for Pocket A, to 99.9% for Circular-Pocket. The Boss and Blind-Step features, used to highlight this sample part, were identified to a precision of 99.0% and 97.7% respectively.



FEATURE	Neural Network Output for Recognition
Boss A	[0 99015]
Boss B	[0 99850]
Blind Step	[0 97734]
Through Hole A	[0 99203]
Through Hole B	[0 99253]
Through Hole C	[0 99253]
Slot	[0 99675]
Protrusion A	[0 99034]
Protrusion B	[0 99553]
Protrusion C	[0 99573]
Step	[0 9966[illegible]]
Circular Pocket A	[0 99980]
Circular Pocket B	[0 97598]
Pocket A	[0 93190]
Pocket B	[0 977[illegible]0]
Pocket C	[0 9710[illegible]]

Figure 2. Sample part used for validation of the system and NN recognition values.

This particular sample part has 224 faces and presents 16 features shown in figure 2 as: (1) Boss (A, B), (2) Blind-Step, (3) Through-Hole (A, B, C), (4) Slot, (5) Protrusion (A, B, C), (6) Step, (7) Circular-Pocket (A, B) and (8) Pocket (A, B, C). Evaluation of the internal characteristics of Boss and Blind-Step features is resumed in Table 1 and the corresponding evaluation of external characteristics in Table 2.

Each feature has particular characteristics that require to be checked. Basically the process consists in calculate or obtain values of each characteristic and compare those values against the values stored in the database. The possible outputs from this checking process is, in first place, that the feature characteristic is 'OK' which means that the particular dimension is acceptable according to the expert's recommendations. In second place, the output could be 'Small' which represents a possible difficulty at manufacturing time, requiring some redesign of the part. The final decision about changes in the design is left to the designer. FEBAMAPP will only give suggestions about which dimensions need to be increased and also some explanations of the possible problems expected if no-change is made in the design.

Table 1. Evaluation of internal characteristics of features in sample part.

FEATURE	INTERNAL CHARACTERISTIC	ACTUAL VALUES	TARGET		STATUS	
			Hand lay-up	Pressure-Bag	Hand lay-up	Pressure-Bag
BOSS	Top-fillet	4	6.4	12.5	Small	Small
	Bottom-fillet	4	6.4	12.5	Small	Small
	Diameter	[illegible]	-	-	-	-
	High	[illegible]	25	-	-	-
	D/H	0.55	2.5	0.5	Small	OK
	Draft - angle	5	2	6	OK	Small
BLIND-STEP	Between-wall fillet	4	6.4	12.5	Small	Small
	Top-fillet	4	6.4	12.5	Small	Small
	Bottom-fillet	4	6.4	12.5	Small	Small
	Draft angle	[illegible]	2	6	OK	Small

Table2. Evaluation of external characteristics of features in sample part.

FEATURE	EXTERNAL CHARACTERISTIC	ACTUAL VALUES	TARGET		STATUS	
			Hand lay-up	Pressure-Bag	Hand lay-up	Pressure-Bag
BOSS	Distance to adjacent feature	[illegible]	[illegible]	[illegible]	OK	[illegible]
		[illegible]	[illegible]	[illegible]	-	-
	Distance to a border					
	Distance to adjacent	[illegible]	[illegible]	[illegible]	OK	[illegible]

BLIND-STEP	feature Distance to a border	45.0	25.0	20.0	OK	OK

Finally, output of the manufacturability analysis module is presented in terms of design recommendations in Table 4. Since there is no way to know the design intention of the part, then it is not advisable to give general recommendations of design for the whole component, and recommendations are focused on each characteristic of the feature.

Evaluation was carried out considering two different manufacturing processes, Hand Lay-Up and Pressure-Bag, so it is possible to observe that the design characteristics required are different upon the manufacturing process selected for the production of the part.

Table 3. Design recommendations according to manufacturing process selected.

FEATURE	DESIGN RECOMMENDATIONS / MANUFACTURING PROCESS	
	HAND LAY-UP	PRESSURE BAG
BOSS	• Top fillet should be increased to avoid problems related to trapped air. Recommended 6.4 mm. • Bottom fillet should be increased to avoid problems related to trapped air. Recommended 6.4 mm. • Ratio Diameter/High should be increased to give more room to tools and facilitate the moulding process. Recommended 2.5 • No problems reported regarding external characteristics.	• Top fillet should be increased to avoid problems related to trapped air. Recommended 12.5 mm. • Bottom fillet should be increased to avoid problems related to trapped air. Recommended 12.5 mm. • Draft angle should be increased to avoid problems related to extracting of the part. Recommended value 6 degrees • No problems reported regarding external characteristics
BLIND-STEP	• Top fillet should be increased to avoid problems related to trapped air. Recommended 6.4 mm. • Bottom fillet should be increased to avoid problems related to trapped air. Recommended 6.4 mm. • Between-walls fillet should be increased to avoid problems related to trapped air. Recommended 6.4 mm. • No problems reported regarding external characteristics.	• Top fillet should be increased to avoid problems related to trapped air. Recommended 12.5 mm. • Bottom fillet should be increased to avoid problems related to trapped air. Recommended 12.5 mm. • Between-walls fillet should be increased to avoid problems related to trapped air. Recommended 12.5 mm. • Draft angle should be increased to avoid problems related to extracting of the part. Recommended value 6 degrees • No problems reported regarding external characteristics.

CONCLUSIONS

The scope of the proposed system is to provide designers with early support in terms of manufacturing capabilities and limitations of available manufacturing processes such that design of reinforced plastic components can be improved from the initial design stages. The analysis approach used in this research focuses on features in the model and attempts to guide the designer in such a manner that internal and external characteristics of those features can be improved reducing global manufacturing difficulties during later stages in the product development process.

A feature-based manufacturability analysis of reinforced plastic components is presented which consists of:

- Automatic identification of the features present in the model
- Evaluation of internal and external characteristic of the features previously identified in the model, and
- A design recommendation output of the system.

Design recommendations are intended to specifically improve each feature instead of attempting to be global design recommendations for the whole component.

The implementation of this system hopefully will reduce the lead-time and enhance the final design reliability of reinforced plastic components.

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A HYBRID NEURAL NETWORKS - FEATURE BASED MANUFACTURABILITY ANALYSIS OF MOULD REINFORCED PLASTIC PARTS

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ABSTRACT

The purpose of this research is to establish a method to perform manufacturability analysis of reinforced plastic components by using a hybrid system including automatic feature recognition and a feature-based assessment of manufacturability.

Feature recognition plays a fundamental role and usually is the first step in downstream activities concerning product development process such as design for manufacturing, design for assembly and process planning.

Critical features to successful reinforced plastic moulding are identified and the relationship between geometric information of the model, expert geometric reasoning, and knowledge of related manufacturing processes are clarified and predetermined together in a useful and efficient manufacturability analysis system.

A prototype system using solid modelling, object oriented programming and a rule-based system, which is intended to consider the fuzziness of the experts reasoning about reinforced plastic components' design, is under construction to test the proposed concepts. The major contribution from this work is a consistent and systematic methodology of analysing the geometry of models allowing assessing its manufacturability. This methodology considers available manufacturing process capabilities, materials and tooling required. Up to now some virtual parts had been used to test the system showing promising results.

Keywords: Feature Recognition, Neural Network, Design For Manufacturing (DFM), Reinforced Plastics, Manufacturability Analysis.

1 INTRODUCTION

The effect of design on manufacture has been subject of frequent research in an attempt to reduce lead time and development costs of new products without sacrificing product quality. The design lead-time can be reduced if manufacturing expert knowledge input occurs throughout the design phase, thus avoiding costly design-redesign loops.

Design for manufacturing (DFM) involves simultaneously considering design goals and manufacturing through the design process starting from conceptual design stage and continuing through the embodiment and detailed design stages. This task is carried out in order to identify and alleviate manufacturing problems while the product is being designed; thereby reducing the lead time for product development and improving product quality [1].

It has been widely recognised that feature-based modelling is a potential medium to link engineering design and manufacturing, and that such a linkage plays a fundamental role in shortening product development cycles. A feature can be defined as *a mathematical function of some topological and/or geometric variables whose values can be readily accessed or derived from the solid model of the part*" [2]. Particularly, manufacturing-related features can be considered as regions of the model with some manufacturing importance regarding materials, processes, tooling and/or labour.

The major difficulty in integrating design and manufacturing lies in providing an effective interface between them [3]. This interface has to be able of providing complete and relevant manufacturing information from the design to the manufacturing domain. In general there are three methods used to transfer this information: interactive feature definition, automatic feature recognition and feature-based design.

Feature definition is process dependent. For this reason moulding reinforced plastics features need to be characterised with the aim of identification and classification. One of the objectives of this work is to point out the capabilities of using a feed-forward Neural Network (NN) as a tool to carry out automatic feature recognition. This will be a first step on the process of evaluating the manufacturability characteristics of a proposed part model.

The concept of classification involves the learning of likeness and differences in patterns that are abstractions of objects in a population of non-identical objects. The recognition of an individual object as belonging to a unique class is called identification. Classification is the process of grouping objects together into classes according to their perceived likeness or similarities. The subject area of pattern recognition includes both classification and recognition and belongs to the broader field of artificial intelligence.

Once features are recognised analysis of manufacturability is performed which considers not only the geometry of the part but also materials, and process capabilities and limitations. It is expected that manufacturing analysis systems will reduce the need of studying and memorising checklists, allowing designers to concentrate their work in the creative aspects of the product development process [illegible]. A systematic methodology for manufacturability analysis will identify manufacture-related problems at the design stage, and provide the designer with the opportunity to correct them early in the process.

The remainder of this paper provides a comprehensive description of the hybrid Neural Network - Feature based manufacturability analysis system proposed. Design representation is discussed first where the structure of the geometrical data of the model is described, followed by a comprehensive description of the concepts used in this research. Next, a sample feature is used to point out design-to-manufacture rules used as basis for the feature-based manufacturability analysis system. Then a description of the manufacturability analysis system framework is presented followed by a validation section where sample parts are used to demonstrate the performance of the system. Finally, a discussion of results and conclusion sections are presented.

2 DESIGN REPRESENTATION

The proposed design representation is based on the boundary representation (B-Rep) of solid modelling. Specifically, design data is retrieved from a CAD system via its Save As Text (SAT) file. SAT files are becoming standard in CAD/CAM software and the part geometry can be designed in any CAD system as long as it can provide an SAT file of the modelled part.

The selected object representation in this work is ACIS, the object-oriented three-dimensional (3D) geometric modelling engine from Spatial Technology Inc. ACIS separately represents the geometry and the topology of the objects, which provides the ability to determine whether a position is inside, outside or on the boundary of a volume. The model is implemented in C++ using a hierarchy of classes.

Geometry of the model refers to the physical entities such as points, edges and surfaces, independent of their spatial relationship. On the other hand, topology refers to the spatial relationship between the entities in the model such as loops and co-edges. Regarding this research, a model object is any object that can be saved to and restored from an SAT saved file. Figure 1 shows the structure of the SAT file.

In this study, the design information is allocated into face-vectors (FVectors), which intrinsically contain model information regarding loops, edges, co-edges, vertices and topological relationships between any particular face and its surrounding faces in the object. These FVectors are connected by a set of link lists, therefore, once a feature is identified it is possible to search the model database and transfer all information regarding faces belonging to a particular feature to the feature-based manufacturing analysis module of the system.

The number of FVectors corresponds to the number of faces in any particular model, and the number of entries in each FVector is nine, one entry for the identified face representing the feature and eight entries for possible surrounding faces. Out of these eight entries, four are reserved for SharingEdge faces and the remaining for SharingVertex faces. SharingEdge face is a face that actually shares an edge with the evaluated face and SharingVertex faces are those that only shares a vertex with it. Since each face has its own FVector, which on expansion contains the information regarding the geometrical and topological characteristics of the evaluated face and its surrounding faces, then it is possible to say that faces with similar characteristics will have similar FVectors, on another words similar patterns. This is the fact used in this study to define different features, where each feature maps to a particular pattern or FVector.

3 RESEARCH CONCEPTUAL FRAMEWORK

3.1 Pattern recognition

A pattern recogniser is a system to which a feature vector is given as input, as which operates on the feature vector to produce an output that is the unique identifier (name, number, code-word, vector, string, etc.) associated with the class to which the object belongs. [5]

An automatic pattern recognition system is an operational system that minimally contains an input subsystem that accepts sample pattern vectors, and a decision-maker subsystem that decides the classes to which an input pattern vector belongs. If it also classifies, then it has a learning mode in which it learns a set of classes of the population from a sample of pattern vectors; that is, it partitions the population into the sub-populations that are the feature classes. Figure 2 depicts sub-populations *S1* to *S4* of a population *P* of non-identical objects, along with the processing that recognises a sample object.

3.2 Concept of Convexity and Concavity

Chuang and Henderson [6] define concavity or convexity of a point on a B-rep element by defining an infinitesimally small spherical neighbourhood with the point at its centre. If the spherical neighbourhood is filled by more than half with solid material, then the point neighbourhood is concave. If the sphere is half filled with solid means that the neighbourhood is smooth, else it is convex. Following the previous definition, a face can be classified as convex or concave. Classification of an edge can be done on the basis of the angle between the faces sharing the edge, can be classified as smooth, convex or concave. A vertex, based on the types of edges sharing the vertex, can be classified as concave or convex. A convex vertex means more convex edges than concave edges sharing it. An illustration of these classifications is shown in Figure 3.

3.3 Concept of FVector

An object in a boundary representation (B-rep) data structure consists of a set of faces and each face has neighbouring faces. In the B-rep scheme for solid models, the definition of the solid comes from combining the geometrical information about the faces, edges and vertices of an object with the topological data on how these are connected. In order to understand the relationship between each face and the other faces of the model, it is possible convert a 3-D object into a 2-D face set [7]. An example of this is presented in Figure 4, where face 1 (F1) of a three-dimensional object is represented in a two-dimensional face set.

In resume, if a value is assigned to edges and vertices based on their geometric and topological information, then these values can be transformed into a score representing the face characteristics. This score includes, implicitly, the face information and the information of the edges and vertices on the face.

The evaluation formula can be written as:

$$F_s = f\,(F_g, E_g, V_g, A_t)$$

Where F_s is the face score. F_g is the face geometry information, E_g is the edge geometry information, V_g is vertex geometry information, and A_t is the adjacency relationship among faces, edges and vertices.

Hwang and Henderson [3] introduce the concept of face score vectors in order to represent features in a suitable way for neural network input, but a modified face score value assignation is used in this research. The reason supporting this modification is based on the presence of fillets that give origin to vertices with four (4) edges and four (4) adjacent faces instead of three (3) edges and three (3) faces as considered by the former authors. The value assignment to each characteristic of the object in terms of faces, edges, and vertices is as shown in Table 1.

Using these values the vertex score is calculated by:

$$V = \sum_{i=1}^{m} E_i$$

Where V is the vertex score, Ei are the scores of the edges that intersect to form the vertex and m is the total number of edges sharing the vertex.

The face score is given by:

$$F = \sum_{i=1}^{n} \frac{V_i}{n} + F_g$$

Where V_i is the vertex score, n is the number of vertices on the face, F_g is the face geometry score.

3.4 Feature definition

According to the previous section, a face score depends on the face and its boundary information. Therefore, since each face in the object has certain face score, a non-zero difference between a face score and its neighbouring face score indicates a topological or geometrical change between these faces, which form a region and the region may be defined as a feature [9]. It is up to the system developers to select the face that better represent each of the features they want to define.

In general, a pattern vector of attributes is converted to a feature vector of lower dimension that contains all of the essential information of the pattern. In this research the conversion process and construction of the FVectors follow the following rules:

- The fifth element of the FVector is the face score of the face under consideration named main face, and corresponding to face F1 in the sample been used.
- The immediately adjacent sharing-edge faces, faces F2, F3, F4 and F5 in Figure 5, with highest scores are in position 4th and 6th, and the next highest in position 3rd and 7th respectively. If there is less than four sharing-edges faces then those empty positions are set to zero. If there is more than four sharing-edges faces then only the four highest scores are considered.
- Next, the highest score of the sharing-vertex faces, faces F6, F7, F8 and F9 in Figure 5, are arranged in positions 2nd, 8th, 1st and 9th accordingly to the same rules applied to sharing-edge faces.

Because faces far away from the main face play a minor role in determining the feature, a nine-element vector is considered to contain enough information for this purpose. The eight features being considered in this paper and their corresponding FVectors are shown in Figure 6.

4 FEATURES AND DESIGN-TO-MANUFACTURE RULES

Design-to-manufacture rules can be seen as critical relationships between design requirements and process capabilities. Process capability data is usually compiled and organised in such a way that constitutes the basis for the design rules. These rules provide with the boundary conditions that determine if a proposed design is feasible from its cost, quality and/or lead-time characteristics.

People in the plastic industry have compiled design rules from process capability data over the last few decades. But, since most of the explicit work in this area is considered as industrial secret, then it was necessary to perform a thorough analysis of mould and die design literature to obtain some detailed information concerning reinforced plastics (RP) product design and manufacture. It is up to the manufacturing and the knowledge engineers to synthesise the rules from process capability data and industrial experience in such a way that can be used in developing a knowledge-based system (KBS) for manufacturability analysis.

The evaluation approach proposed in this research considers in first place internal characteristics of the feature in terms of dimensions, thickness, fillet radii and draft angle. In second place, external characteristics consider position of the feature in relation to another features in the part and in relation to the boundary edges of the part. Attention is focused in the manufacturability aspects according to the capabilities and limitations of the available reinforced plastics manufacturing processes (RPMP).

The series of features to be evaluated during the manufacturability analysis are pocket, protrusion, circular-pocket, boss, through-hole, slot, step and blind-step. All of them fully supported by the automatic feature recognition module developed as part of this research [10].

4.1 Sample Feature (Pocket Feature)

Due to limitations of space in this paper the pocket feature will be used as a sample feature to describe the considerations made to perform the feature-based manufacturability analysis of a particular model. Similar analysis is made for each feature under consideration.

Any hollow in the surface of the part can be considered as a pocket feature. The shape of this cavity can be rectangular, elliptical, or irregular. Circular shape is considered as a particular feature called C-Pocket. The internal characteristics to be considered for evaluation of a pocket are its depth, radii of the bottom and top fillets, radii of between-walls fillets, and draft angle as shown in Figure 7.

The minimum depth of a pocket is driven by the manufacturing process to be used according to recommended top and bottom fillet radii given on Table 2 [11]. It is recommended to use a constant and homogeneous radio through the feature to avoid blending two or more adjacent faces using a spline surface. Spline surfaces are not easy to build and even though numerical controlled machines can follow this kind of surface it will, unnecessarily, increase the cost of the final mould. Otherwise, when the same fillet radii is used, per example, in all three cone surfaces converging into the bottom corner of a pocket feature, a concave sphere surface is created, which is more easy and economical to construct.

The top corners of the pocket present a different situation, where it is necessary to blend two convex and one concave cone-surface. In this particular case does not matter what combination of radii are used always the blended surface in the corner will be a four-side spline surface. From the manufacturing point of view this situation is not a problem as long as the top edge fillet be kept constant all around the pocket feature. These rules and recommendations regarding between-walls, top and bottom fillets apply to all features with similar geometric configurations, as step and blind-step.

The appropriated draft angle depends on the material selected and minimum recommended values are given in Table 3. From the manufacturing point of view. it is necessary to check that the draft angles are appropriated in each vertical wall of the model. therefore the intended direction for pulling out the part is required, so each vertical wall can be evaluated on its own. The normal vector to the surfaces is used as reference to evaluate the angle between the vertical walls and the pulling-out direction of the mould, assumed to be the Z-axis in all cases.

Regarding the external characteristics of the pocket feature the most important to be considered are allowance to tool reach, closeness to adjacent features and closeness to the boundary edges of the part. It is necessary at this point to make reference to the fact that different RPMP might have different requirements for external characteristics of features.

If the process to use is hand lay-up or spraying, then the reverse side shows the surface where the material will be laid-up. The tool-gap recommended for those two processes requires a minimum distance between two opposite vertical walls such that the laying-up and rolling tasks can be performed without interference. According to typical tool sizes available in the market and to the minimum radii at the bottom fillets of the gap. the minimum distance recommended is 13 mm at the bottom of the gap between the pocket feature and any other adjacent feature or external boundary of the part

For pressure bag process the tool gap required is even larger, since the elastic bag is limited in its flexibility and it will not be able to reach the bottom of gaps smaller than 25 mm and depth grater than 35 mm. It would be possible to use deeper pockets as long as enough gap is provided between the vertical walls of the pocket and the adjacent features or external walls of the part.

For matched-die processes the tool-gap is limited mainly by the kind of reinforcement used and properties of the resin. There are some resins that flow easily but some others require vacuum and/or pressure assistance to be able of reach fine details in the mould.

Regarding the draft angle, the depth of the vertical walls affects it, and this angle can be defined according to Table 4 for some of the available RPMP.

Same procedure is followed for each one of the features considered in this research, such that information regarding feature internal and external characteristics was collected and a set of design-to-manufacture rules was created for each feature. These rules are used as the basis for the manufacturability analysis system.

5 THE MANUFACTURABILITY ANALYSIS SYSTEM FRAMEWORK

Figure 8 presents the framework of the Feature-Based Manufacturability Analysis of Plastics Parts (FEBAMAPP) system. The system evaluates the model starting with the pre-processing of the text file of the part (ACIS file), goes through automatic feature recognition, evaluation of internal and external characteristics of all features identified and end up with a feed-back to the designer in terms of design suggestions. Design suggestions are focused on those features, which may represent problems at manufacturing stage and they do not attempt to be general design suggestions for the whole model.

The product concept development process is rather complex that requires a set of assumptions to simplify the task. The assumptions included in this system are that the market has been analysed, the need for a new product has been identified, design requirements and product constraints have been defined, and the functions of the mould reinforced part or components have been identified based on design requirements and product constraints. The FEBAMAPP system focuses on evaluating proposed models at the early stage of the product development process using a rule-based expert system.

5.1 Knowledge-Based System Design

According to the human experts, the types of knowledge related to reinforced plastics manufacturing processes are usually represented in forms of equations, tables, rules of thumb and design constraints related to materials and/or processes. The frame-based representation method is used in FEBAMAPP to present the knowledge of a particular feature (object); while the rule-based knowledge representation is used to represent the decision logic and features mapping.

The declarative knowledge or facts used in FEBAMAPP can be broadly classified as follows.

- Feature knowledge (design constraints).

- Plastic material knowledge (matrix).
- Reinforcing material knowledge (fibre).
- Equipment and tooling knowledge (processes).
- Mould components design knowledge.

The rules can be broadly categorised as follows.

- Rules for material selection.
- Rules for process selection.
- Rules for evaluation of internal characteristics of features.
- Rules for evaluation of external characteristics of features.

LPA-FLEX, an Expert System (ES) shell implemented in Prolog is used to develop FEBAMAPP rather than to construct a new ES environment from scratch. The inference engine of the system draws upon both the stored knowledge and replies from the user of the system in order to reason its way through to an answer. Typically, design applications use the forward chaining instead of backward chaining based upon its simplicity and better efficiency in execution. The inference process begins with the information currently provided by the pre-processing of the SAT file of the solid model of the part and draws conclusions, according to the conditional rules that it knows already. During this process, it may request further details from the user so proper selection of materials and manufacturing process can be used during the inference process. Eventually, it will arrive at logical consequences, which it then gives as its decision and a report in terms of design suggestions is generated.

5.2 THE PROTOTYPE SYSTEM

A prototype system was developed according to the framework presented above and it consists of several modules as follows.

- Pre-processing of Sat file (PRESAT).
- Automatic feature recognition (AFR).
- Post-processing of the Sat file (POSTSAT).
- Material selection (MS).
- Process selection (PS).
- Manufacturability analysis (MA).
- Report generation (RG).

The system is designed to run the modules in sequential order. Modular reports of partial results from each module are available to the designer if required.

6 VALIDATION OF THE SYSTEM

Validation of the system was made using virtual sample parts and promising results have been found. Figure 9 shows one of those sample parts where it is possible to observe the presence of several features, which are previously identified by the feature recognition module in the manufacturability analysis process. Table 5 shows neural networks results of the recognition process for each feature present in the sample part.

This particular sample part has 166 faces and presents 12 features identified in figure 9 as: (1) Boss, (2) Blind-Step, (3) Through-Hole (A, B, C), (4) Slot, (5) Protrusion (A, B), (6) Step, (7) Circular-Pocket and (8) Pocket (A, B). Evaluation of the internal characteristics of Boss and Blind-Step features is resumed in Table 6 and the corresponding evaluation of external characteristics in Table 7. Finally, output of the manufacturability analysis module is presented in terms of design recommendations in Table 8, which are focused on each feature.

Evaluation was carried out considering two different manufacturing processes, Hand Lay-Up and Pressure-Bag, so it is possible to observe that the design characteristics required are different upon the manufacturing process selected for the production of the part.

7 CONCLUSIONS

From the results of this work, it can be concluded that neural networks can be used as part of an automatic feature recognition system of manufacturing features of reinforced plastic components.

It is necessary to train one neural net for each feature to be recognised, which make the system easy to expand for the recognition of a major number of features or more complex ones if required. This would increase the time required to evaluate a particular part, since each face of the part has to be presented to each net for a particular feature recognition, but it will simplify the architecture and training of the system. High performance of the system was evident during the feature recognition stage for the sample parts used in this work, where all trained features were recognised.

In order to integrate available RPMP's knowledge into a manufacturability analysis system, it is necessary to define the boundaries and the scope of such system. Manufacturing processes, techniques, tools and materials usually set these boundaries. Furthermore, empirical rules and heuristic knowledge developed by designers and manufacturers working in the reinforced plastic industry help to set the proper frame for such manufacturability analysis.

The scope of the proposed system is to provide designers with early support in terms of manufacturing capabilities and limitations of available manufacturing processes such that design of reinforced plastic components can be improved from the initial design stages. The analysis approach used in this research focuses on features in the model and attempts to guide the designer in such a manner that internal and external characteristics of those features can be improved reducing global manufacturing difficulties during later stages in the product development process.

A feature-based manufacturability analysis of reinforced plastic components is presented which consists of:

- Identification of the features present in the model
- Evaluation of internal and external characteristic of the features present in the model, and

- A design recommendation output of the system. Design recommendations are intended to specifically improve each feature instead of attempting to be global design recommendations for the whole component.

The implementation of this system hopefully will reduce the lead-time and enhance the final design reliability of reinforced plastic components.

8 ACKNOWLEDGEMENT

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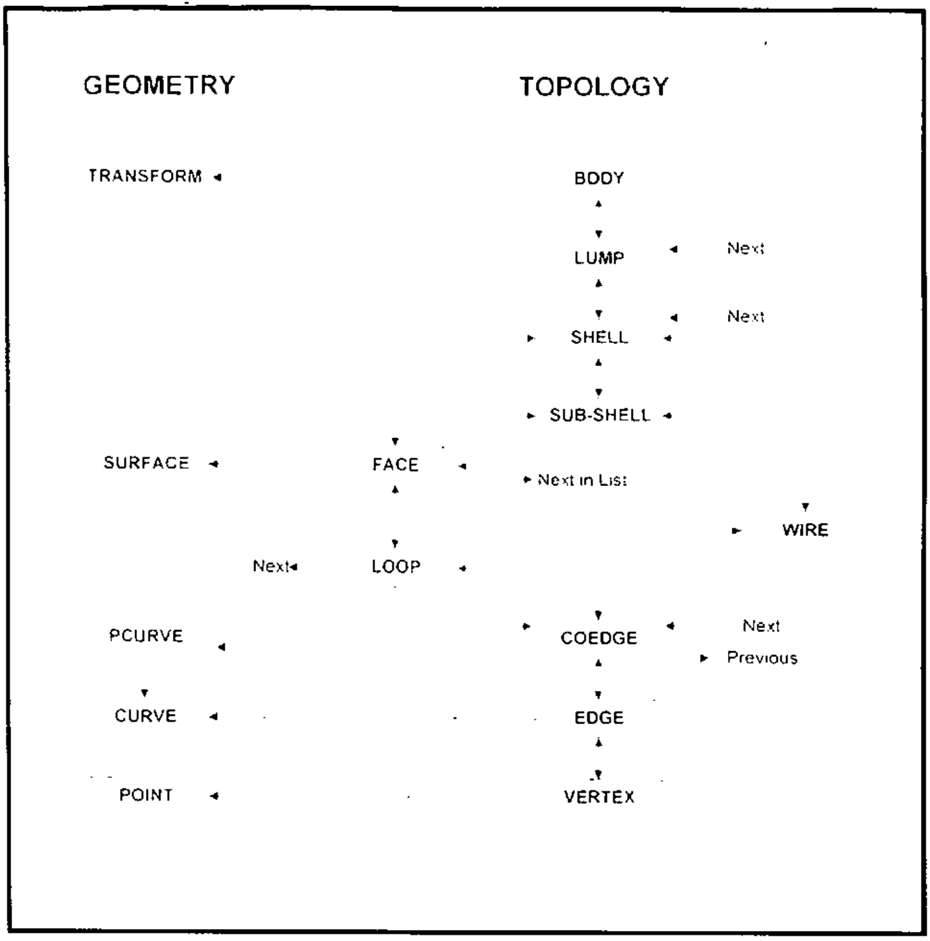

Figure 1. SAT file geometrical and topological structure.

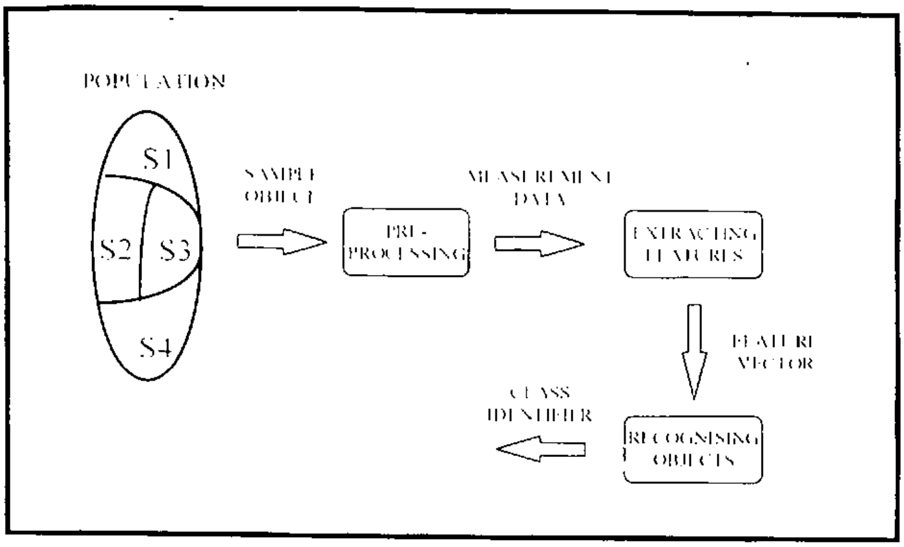

Figure 2. The recognition/classification process.

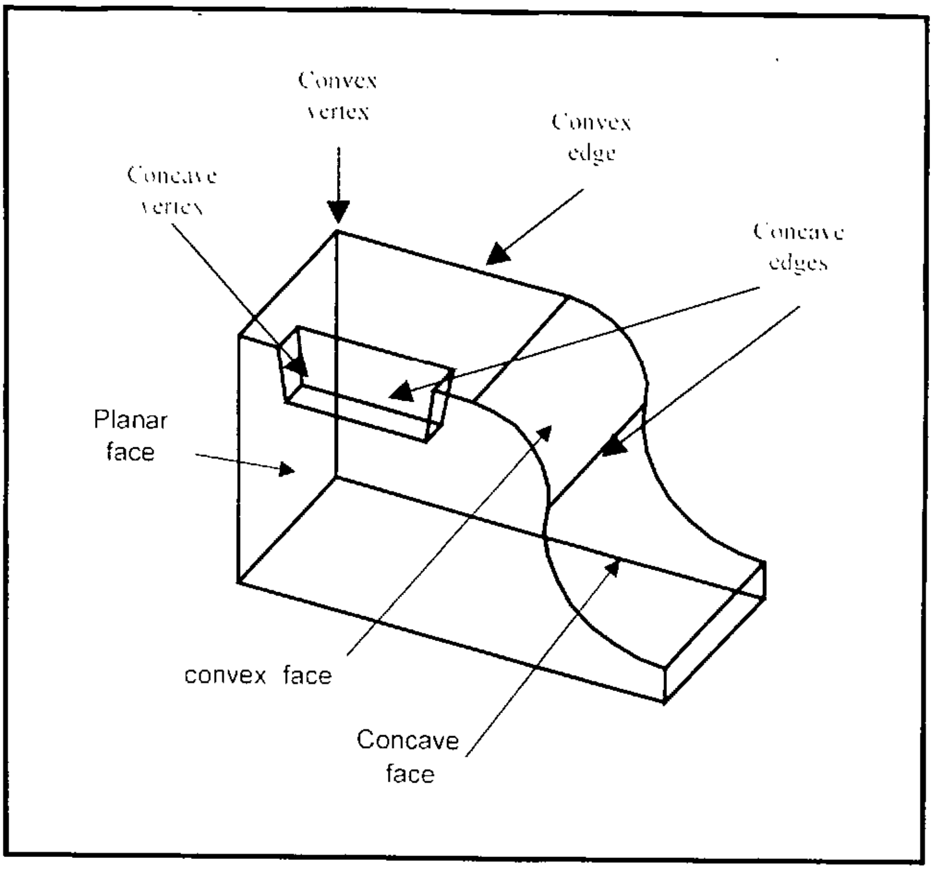

Figure 3. Face, edge and vertex classification.

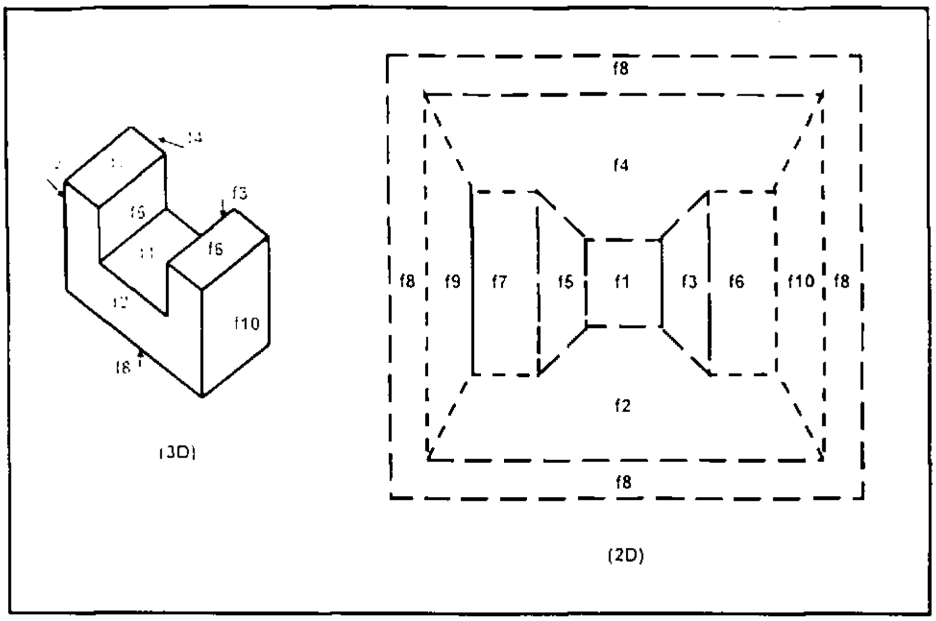

Figure 4. Two-dimensional (2D) representation of a three-dimensional (3D) object

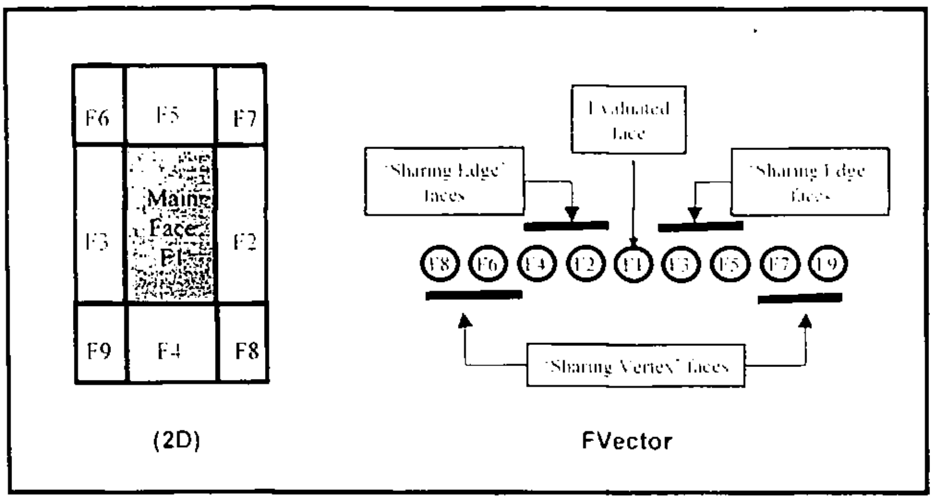

Figure 5. 2D representation of a 3D object and FVector corresponding to face 1.

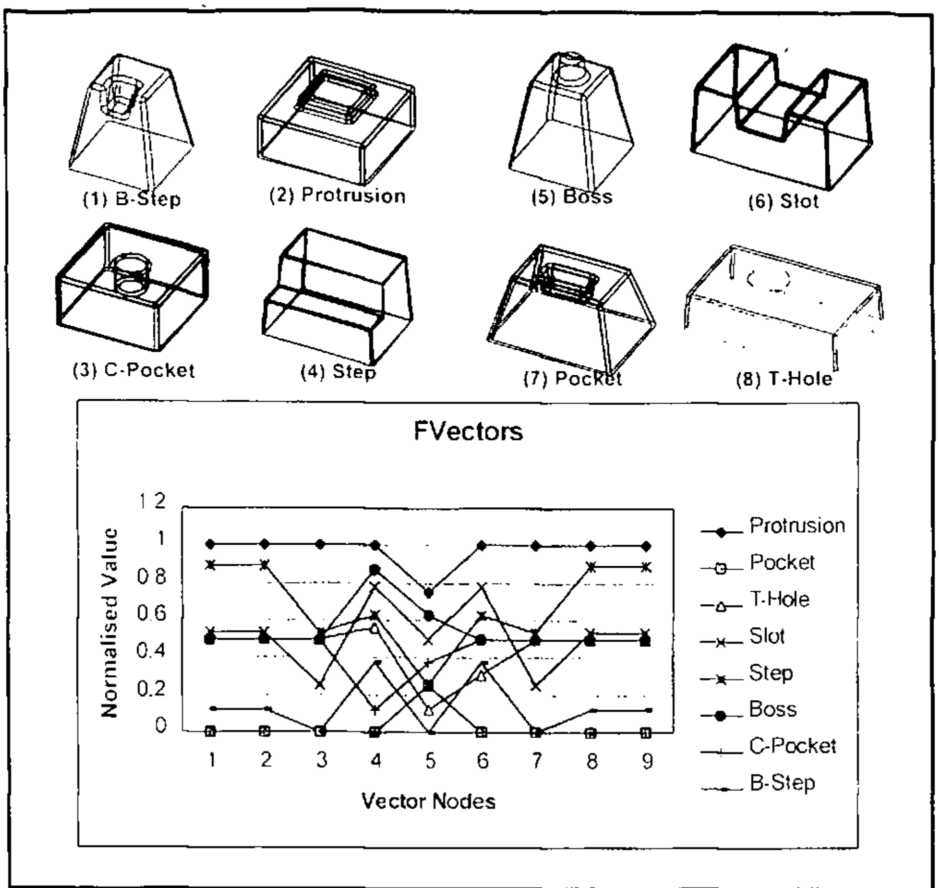

Figure 6. Features and their corresponding Fvectors.

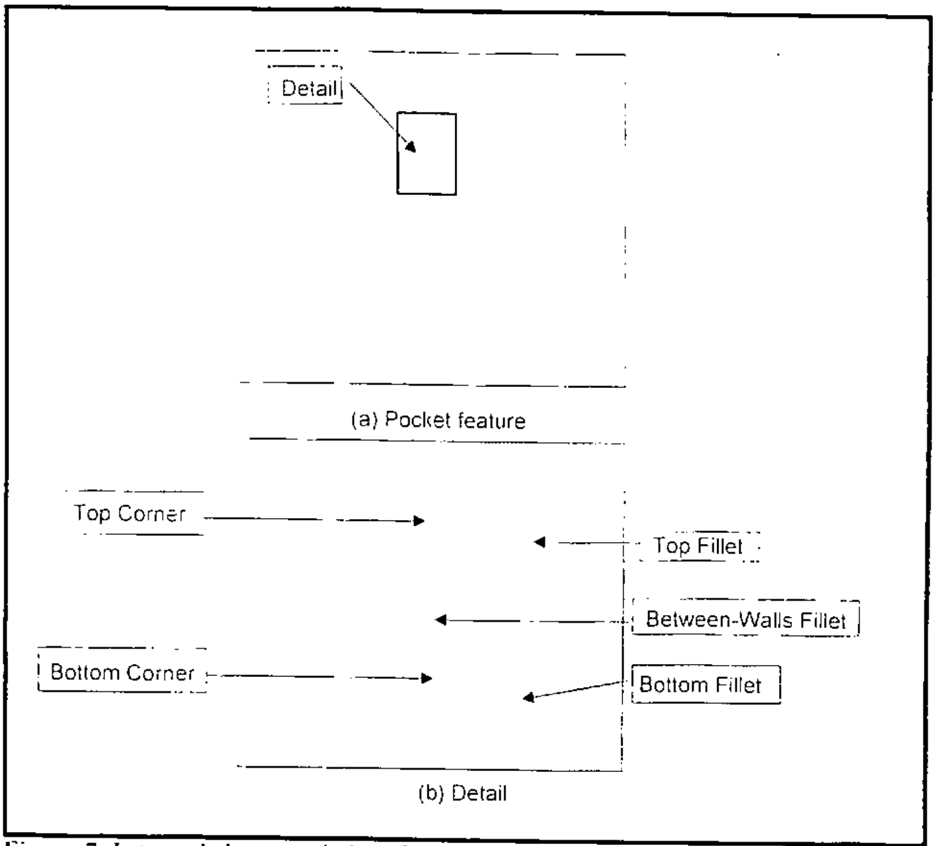

Figure 7. Internal characteristics of the Pocket feature.

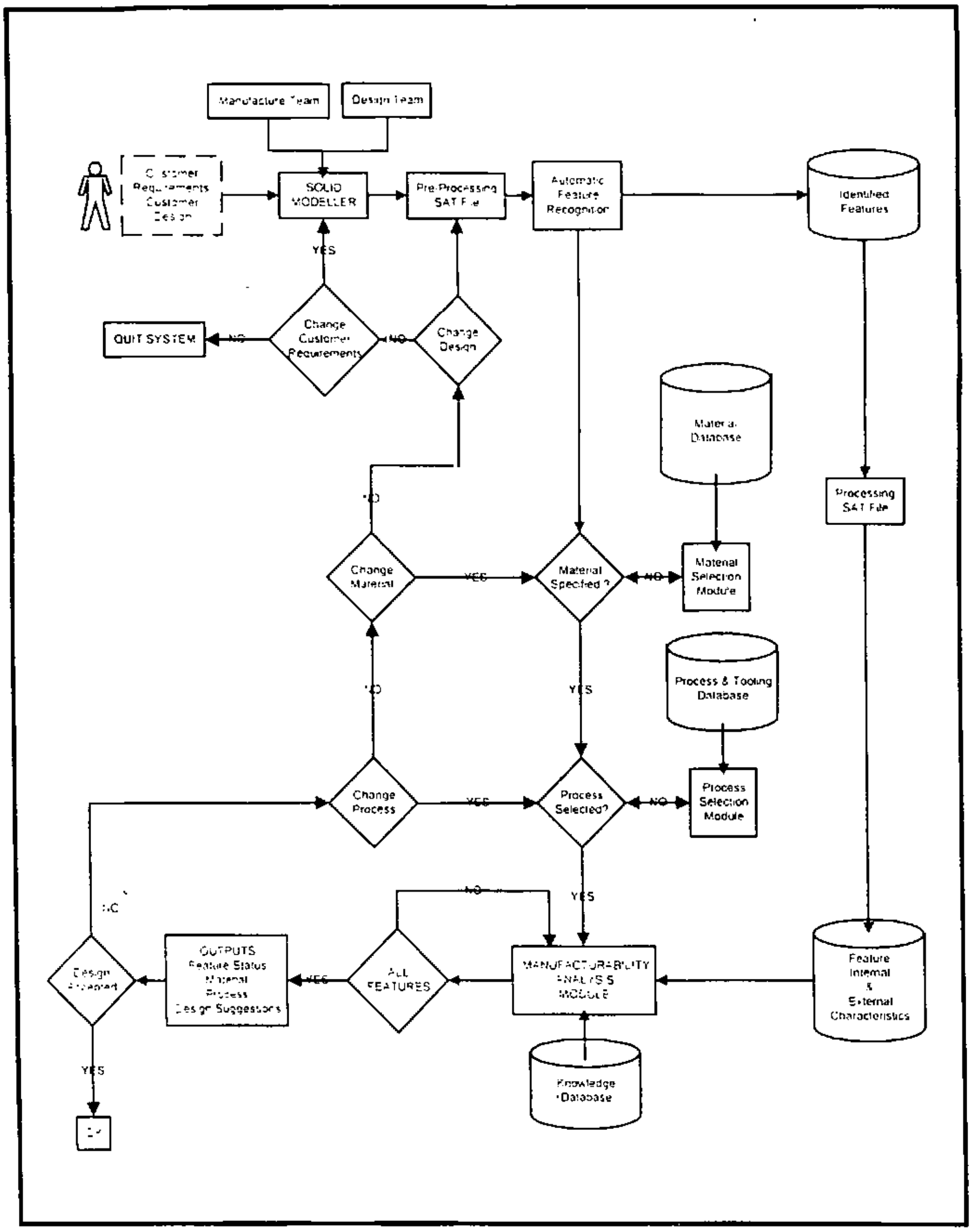

Figure 8. Framework of the FEBAMAPP system.

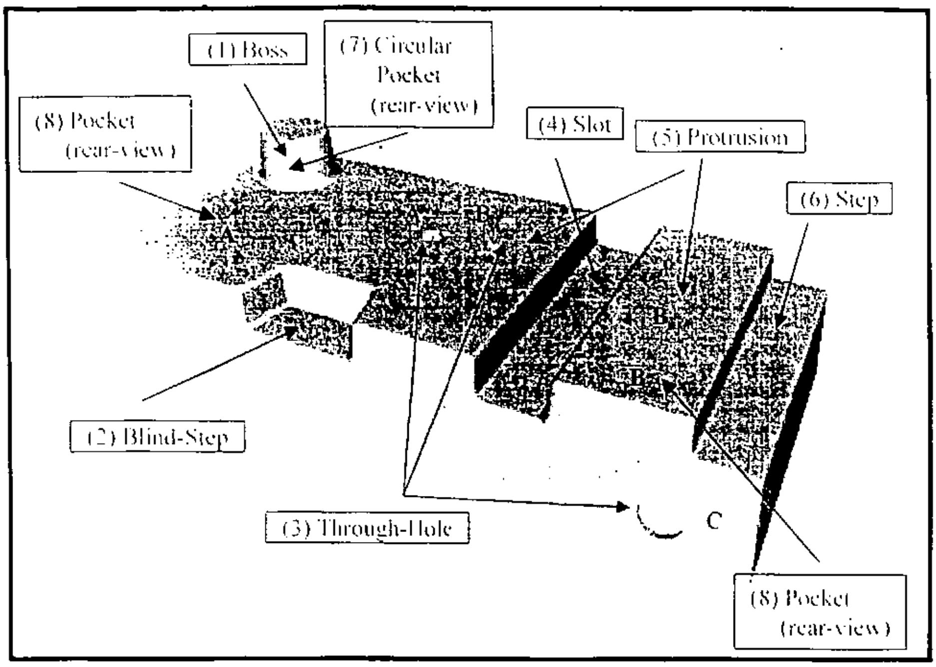

Figure 9. Sample part used for validation of the system.

Table 1. Assignation of values to obtain face values.

Edge Scores (E)	
Convex edge	+ 0.5
Concave edge	- 0.5
Face Geometry Scores (F_g)	
Planar surface	0.0
Convex surface	+ 2.0
Concave surface	- 2.0
Spline surface	0.0

Table 2. Recommended minimum radii according to RPMP to be used.

PROCESS	RADII (mm)
Hand laying-up	6.40
Spraying	6.40
Pressure bag	12.50
Filament winding	3.20
Dough Moulding Compound (DMC)	0.75
Matched die, pre-form mat	3.20

Table 3. Minimum draft angles recommended for particular materials

Thermosetting materials	Draft angles
Alkyd	0 5 – 1 0
Epoxy glass	0 5 – 1 0
Phenolic	0 5 – 1 0
Silicon glass	0 5 – 1 5
Polyester	0 5 – 2 0
Thermoplastic materials (*)	
ABS	1 0 – 2 0
Nylons	0 5 – 1 5
Acetal	0 5 – 1 0
Polyethylene	0 25 – 2 0
Polypropylene	0 25 – 1 5
Polystyrene	0 25 – 1 5
PVC	0 5 – 1 0
Polyurethane	0 25 – 1 5

Table 4. Recommended draft angle for vertical walls according to several RPMP. [Angle in degrees]

PROCESS	WALL DEPTH [mm]				
	0 - 25	20 - 50	40 - 200	150 - 500	500 - more
Hand laying-up	1	2	3	5	7
Spraying	1	3	5	8	10
Pressure bag	5	6	8	10	12
(DMC)	1	1	1	2	2
Matched die. pre-form mat	1	2	2	3	5

Table 5. Neural Network (NN) Output for feature recognition.

FEATURE	Target Neural Network Output	Actual Neural Network Output
Protrusion A	[1.00]	[0.99034]
Protrusion B	[1.00]	[0.99663]
Boss	[1.00]	[0.99015]
Blind-Step	[1.00]	[0.97734]
Circular Pocket	[1.00]	[0.99875]
Pocket A	[1.00]	[0.93190
Pocket B	[1.00]	[0.97710]
Through Hole A	[1.00]	[0.99203]
Through Hole B	[1.00]	[0.99253]
Through Hole C	[1.00]	[0.99253]
Step	[1.00]	[0.99661]
Slot	[1.00]	[0.99675]
Circular-Pocket	[1.00]	[0.99980]

Table 6. Evaluation of internal characteristics of features in sample part.

FEATURE	INTERNAL CHARACTERISTIC	ACTUAL VALUES	TARGET		STATUS	
			Hand lay-up	Pressure-Bag	Hand lay-up	Pressure-Bag
BOSS	Top-fillet	4	6 4	12 5	Small	Small
	Bottom-fillet	4	6 4	12 5	Small	Small
	Diameter	30	-	-	-	-
	High	35	25	-	-	-
	D/H	0 86	2 5	0 5	Small	OK
	Draft - angle	5	2	6	OK	Small
BLIND-STEP	Between-wall fillet	4	6 4	12 5	Small	Small
	Top-fillet	4	6.4	12 5	Small	Small
	Bottom-fillet	4	6 4	12 5	Small	Small
	Draft angle	5	2	6	OK	OK

Table 7. Evaluation of external characteristics of features in sample part.

FEATURE	EXTERNAL CHARACTERISTIC	ACTUAL VALUES	TARGET		STATUS	
			Hand lay-up	Pressure-Bag	Hand lay-up	Pressure-Bag
BOSS	Distance to adjacent feature	35.0	25.0	20.0	OK	OK
	Distance to a border	NA	25.0	20.0	-	-
BLIND-STEP	Distance to adjacent feature	40.0	30.0	20.0	OK	OK
	Distance to a border	45.0	25.0	20.0	OK	OK